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Acoustic monitoring of a prestressed concrete beam reinforced by adhesively bonded composite

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ABSTRACT: The use of adhesively bonded composite reinforcement is relatively widely used for concrete structures. Yet, some questions remain regarding its use in the case of prestressed concrete structures especially in relation with the influence of existing cracking and the verification of the encountered damage phenomena at real scale. French National Organism Cerema with the help of French motorway bridge owners association ASFA and French National Research Organism IFSTTAR realized several real size experimental investigations of an old prestressed concrete beam coming from a deconstructed bridge to answer these questions (Project CLERVAL). Both flexure and shear tests up to failure were carried out and several measurement methods were used to understand the role of the composite reinforcement on the behavior of the structure and the damage scenario. Acoustic emission was one of these methods and two different systems were investigated. The proposed communication will first describe the two used acoustic systems and their dedication. A specific development will then be presented aiming at optimizing the obtained acoustic phenomena localization. Finally, main results will then be presented for both flexure and shear tests. The obtained results are currently compiled with the results from the other measurement methods. This should allow to better understand the damage process of reinforced prestressed concrete beams and to assess the precision of existing reinforcement design methods.

1 DESCRIPTION OF THE PROJECT “CLERVAL”

In France, many precast prestressed concrete beam bridges were built in the 1970s. They may suffer from the corrosion of the prestressed cables and from a lack of passive reinforcement that may induce brittle failure. In addition, the traffic increase may require their strengthening. For all these situations, the use of adhesively bonded composite reinforcement represents a good alternative to realize the required reinforcement or to ensure structural safety (AFGC, 2011; Benzarti et al., 2011).

Though many studies have been carried out to check the adequacy of such reinforcement methods, there are still some issues regarding reinforcement of damaged prestressed concrete beams with existing cracks. There are also very few real scale tests, more particularly on aged beams and it was consequently decided to carry out such a test in a project called “CLERVAL”. This project was led by CEREMA (National centre for studies and expertise on risks, environment, mobility and urban and country planning) in collaboration with ASFA (French motorway owners association) and IFSTTAR (French Institute of Science and Technology for Transport, Development and Networks.

1.1 Presentation of the beam being tested

The used prestressed concrete beam comes from a viaduct over the river Doubs at Clerval that was erected between 1952 and 1954 and demolished in 2002. This beam was 30 m long and 1.3 m high and it had two initial bend cracks with a maximum opening of 0.2 mm (sections S2 and S4). Prestressing cables are not straight and their position is not symmetric (figure 1). The prestressing system is STUP 12 Phi5.

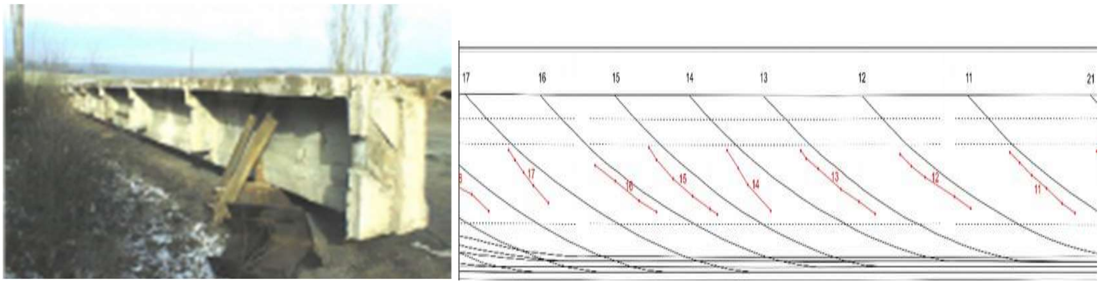


Figure 1. Photo of the studied beam and scheme of the prestressing cables position on one side of the beam

Several investigations took place on the beam before the realization of the test program to identify existing defects, characterize the concrete, check the exact reinforcement and prestressing cables position and amount, assess residual prestress level and prestressing ducts injection quality (Houel et al., 2015).

1.2 Test program

In order to obtain a maximum of information from the realized investigations, the test program was divided in several steps.

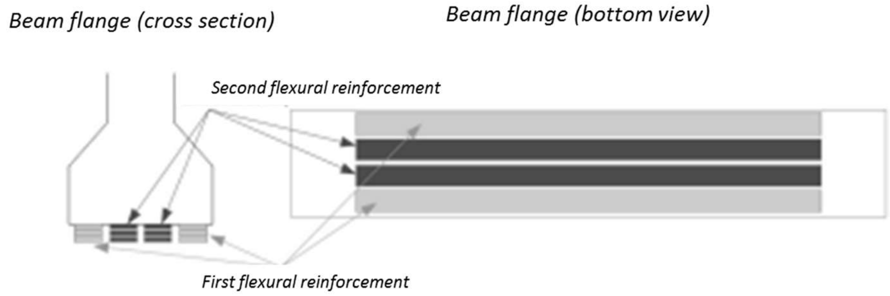


Figure 2. Scheme of the flexural reinforcement applied on the flange of the beam

First steps were dedicated to the study of flexural reinforcement (using adhesively bonded pultruded composite lamellas: 50 x 1.2 mm², 165 GPa) (Figure 2) in 3-point bending configuration (span: 29.34 m and force applied 12.9 m from support) and included:

- First loading before reinforcement (up to 240 kN): This phase allowed identifying and localizing crack activation along the beam.
- Loading after first flexural reinforcement (2*3 50 mm wide plates) (up to 300 kN): This phase allowed studying the role of flexural reinforcement in cracked sections. After this series of test, reinforcement was cut at section S2 in order to decrease locally the capacity of the beam.

- Loading up to failure after second flexural reinforcement (4*3 50 mm wide plates) (up to 614 kN): This allowed identifying the failure process and assessing predictive approaches.

Second steps were realized on third of the beam and dedicated to the study of shear reinforcement (using adhesively bonded carbon sheet: five 150mm-wide U-sheets with a spacing around 300 mm, and one specific horizontal edge reinforcement, 105 GPa) in 3-point bending configuration (span: 9.7 m, and force applied at 1.54 m from support) and included:

- First loading (up to 1100 kN): This phase allowed identifying and localizing crack activation along the beam.
- Second loading after additional reinforcement up to failure (up to 1970 kN): this allowed identifying failure process and its localization.

1.3 Monitoring during the test

Many different monitoring systems were settled on the beam during the different test steps in order to be able to compare modeling or design theories with the actual beam behavior with or without composite reinforcement. More traditional sensors included rotation, temperature, resistive strain, crack opening, and displacement sensors. Less usual systems were also applied as curvature measurement, optical fiber strain measurement, and acoustic techniques. The present article focuses on the results obtained with this last method. Two different acoustic systems were used and are described in the next part.

2 DESCRIPTION OF THE USED ACOUSTIC SYSTEMS

2.1 Overall acoustic survey

The first acoustic system that was applied for each test up to failure aimed at investigating the overall failure process focusing on high energy release phenomena detection. The system is currently used for cable-stayed bridges survey in France (Le Cam et al., 2009) and is commercialized by A3IP. It relies on the use of accelerometer sensors with a natural frequency of 22 kHz, and a specific synchronizing system Pegase. The system allows obtaining 1D localization of high energy phenomena mostly encountered at steel wire failures. The detection threshold was fixed at 2G and three sensors must detect the phenomenon before obtaining an acoustic event.

The maximum distance between sensors was fixed on site at 3.5 m. 7 sensors were used in the case of the flexural test (Figure 3). 10 sensors were used in the case of the shear test (Figure 3). In this last case, an additional work was carried out to dispose of 2D localization of the events as many events occurred close to the edge where prestressing cables are curved (Figure 1).

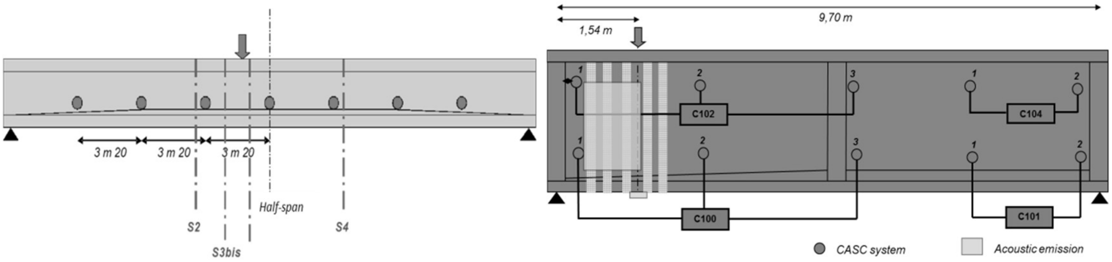


Figure 3. Disposal of CASC sensors along the beam for flexure (on the left) and shear (on the right) tests

2.2 *Localized acoustic emission*

The localized acoustic emission system used during this test is a commercialized by MISTRAS and relies on the use of piezoelectric sensors having a natural frequency of 150 kHz. The system allows the synchronization of up to 16 sensors and 2D localization of the events. A threshold of 35 dB was used and the speed of acoustic wave was calibrated before each test campaign. Other acoustic parameters were chosen according to experience obtained in experimental campaigns in (Rossi et al., 2012) and (Ramadan et al., 2008).

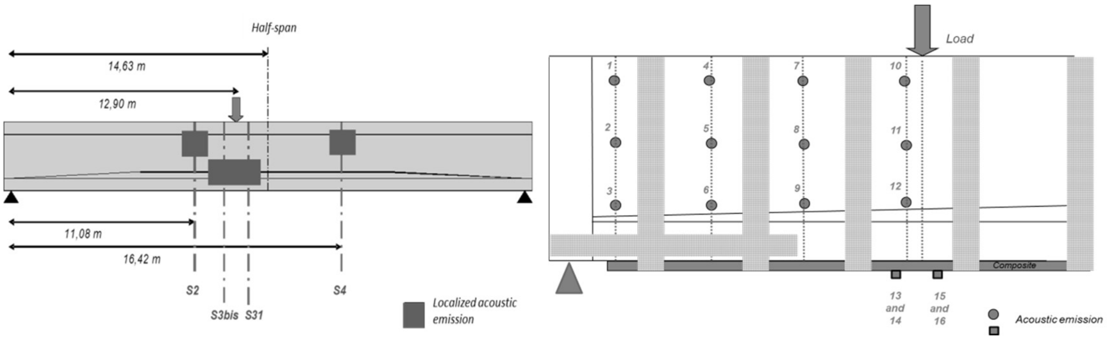


Figure 4. Disposal of localized acoustic emission sensors for flexure (on the left) and shear (on the right) tests

In the case of the flexure test, 3 zones were more particularly studied: sections S2 and S4 above areas where cracks were identified and section S3/S31 (Figure 4). In the case of the shear test, the edge zone reinforced with composite and between the applied force and the support was more particularly studied.

3 MAIN RESULTS OBTAINED DURING FLEXURE TESTS

It will not be possible to present here all the results from the flexural test campaign. Yet, several main results from both systems will be highlighted to address the potentiality of these methods and their comparison with more traditional monitoring systems.

3.1 *Identification of the crack activation using localized acoustic emission*

In the case of flexural tests, the localized acoustic emission system was mainly aimed at identifying the crack propagation in pre-determined cracked areas (sections S2 and S4). Though, from calculation, during flexural test before reinforcement, crack propagation should have occurred first in section S2, it was proved that it actually started in section S4. This was detected both from acoustic emission, crack opening sensor and strain gage measurements. It was checked that the localization of acoustic events was similar to the visual crack identification made after the initial flexural test (Figure 5).

Besides, for the three flexural phases, acoustic emission data was compared with crack opening measures (Figure 6). It can be seen that both are not always correlated. Acoustic emission allows following crack propagation, though crack opening measure may not induce crack propagation. It can also be seen that the reinforcement has slightly delayed the onset of crack propagation. Acoustic emission technique seems thus to be a good indicator to check the activity of a crack on-site and to detect the crack tip localization. It may also be used to assess the quality of reinforcement or repair.

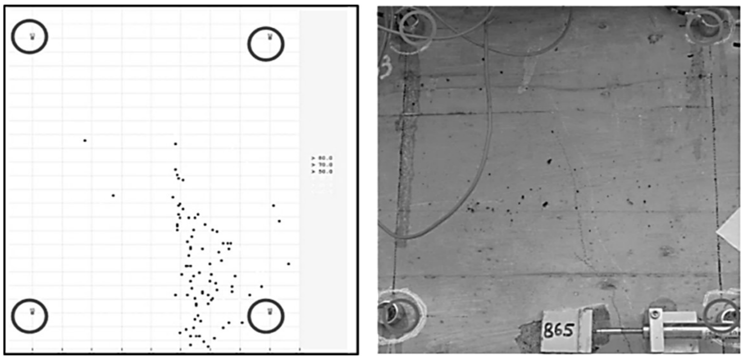


Figure 5. Comparison of 2D localization of events and the visual crack identification after the test at S4 section during initial flexure tests

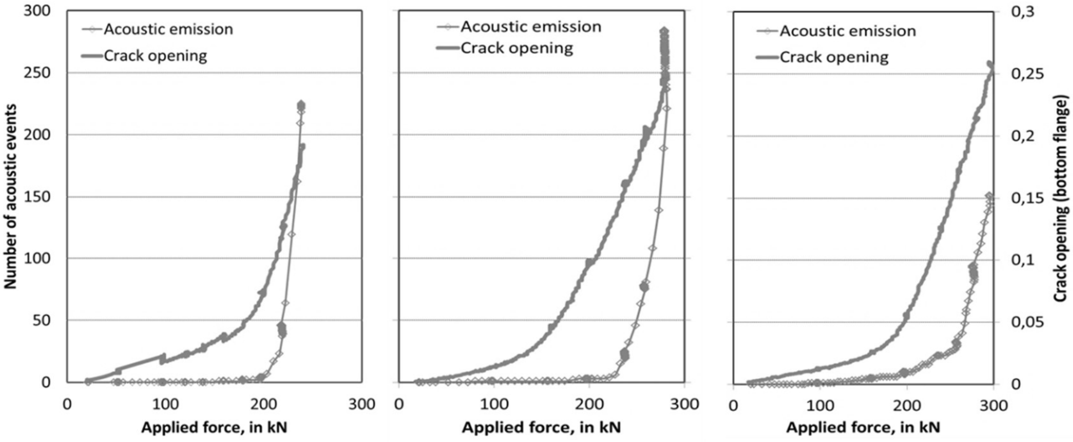
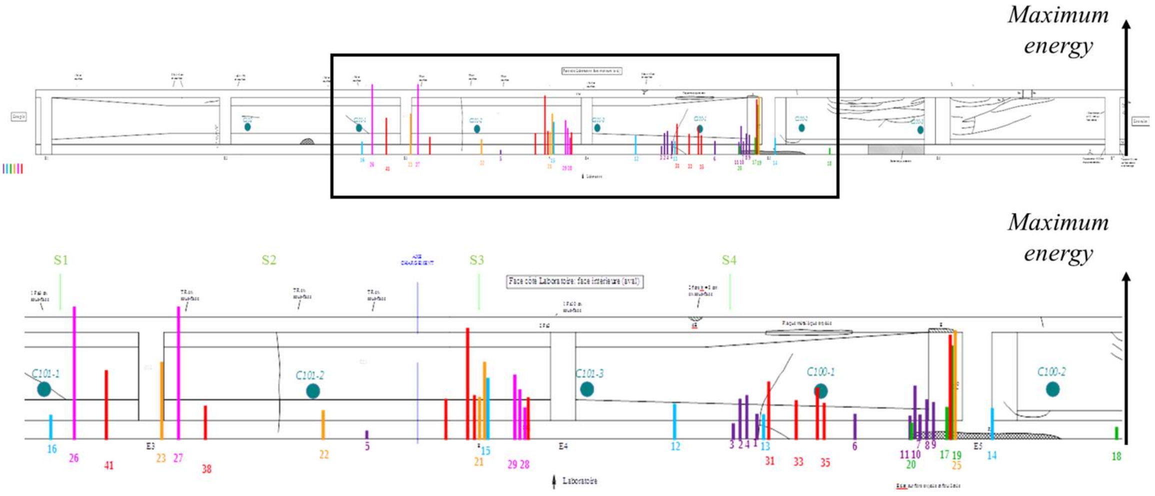


Figure 6. Number of acoustic events and measured crack opening in function of the applied force before reinforcement, after first flexural reinforcement and after final flexural reinforcement at section S4

3.2 Identification of the failure process using overall acoustic survey

The overall acoustic survey with CASC system was carried out during the final test up to failure. It allows detecting main acoustic events and proposing corresponding failure phenomenon depending on the measured parameters (number of sensors detecting the event, wave speed, maximum amplitude). To do this, it was decided to rely on the methodology proposed in (Robert et al., 1999) to determine events corresponding to one prestressing steel wire failure, several prestressing steel wires failure and a bunch of prestressing steel wire failures).

All the 1D localized events with the corresponding energy have been reported on figure 7. First events were detected from 400 kN to 480 kN in section S4 and in a section where corrosion was detected before the realization of the test. It seems that the encountered failures of prestressing steel wires induced a strong change in the behavior of the beam. Then, several prestressing steel wires broke before the final failure that occurred at 615 kN (composite peeling-off in section S2). Acoustic survey allowed with the other monitoring devices to determine the failure process. All the detected acoustic events seem in that case to be attributed to prestressing steel wires failures (when composite peeling-off occurred the beam was maybe too much damaged for the acoustic system to detect it).



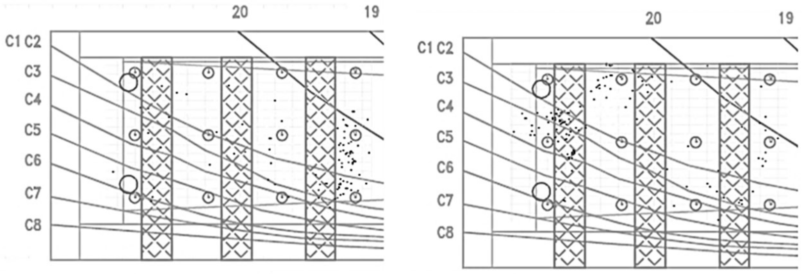
(From left to right : purple from 400 to 480 kN, blue from 480 to 520 kN, green from 520 to 590 kN, orange from 590 kN to ultimate force, pink and red end of the test)

Figure 7. 1D acoustic events along the beam during flexure test

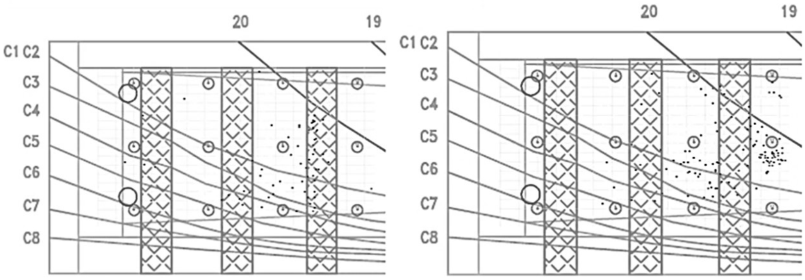
4 MAIN RESULTS OBTAINED DURING SHEAR TESTS

It is important to note that the shear test was carried out on one third of the previous beam that had already been submitted to flexural test up to failure. Yet, the test has been made on a part at the edge that has been little damaged and where no major acoustic event has been detected.

4.1 Identification of the damage in the edge zone using localized acoustic emission



Up to 1700 kN   *From 1700 kN to 1900 kN*



From 1900 kN to ultimate laod   *End of the test*

Figure 8. Localized acoustic emission events during shear test up to failure (carbon sheets and prestressing cables are visualized)

The localized acoustic emission system was settled in the reinforced area between the load application and the support. It allowed localizing the acoustic events during the shear test in this area during the whole test (Figure 8). Four main periods were determined. During the first period up to 1700 kN, acoustic events mainly occurred under the load application demonstrating flexure damage rather shear damage. At the end of this period, flexural composite plates peeled-off. From 1700 kN to 1900 kN, most of acoustic events were detected in the corner close to the edge. This corresponds to a crack that was visually detected at the end of the test in this zone. From 1900 kN to the ultimate capacity (1970 kN), the acoustic emission was gain localized under the applied load. At failure, a main crack was observed under the applied load.

Though, some investigations are still under progress, acoustic emission allowed in that case identifying different failure steps during the test. The results were compared with visual inspection led during and after the test and good match was obtained. However, no particular acoustic emission could be revealed under the bonded carbon sheets indicating though high mechanical stresses have been measured on them with strain gages.

4.2 Identification of the failure process using overall acoustic survey

In the case of the shear test, two lines of 5 sensors have been disposed along the beam (Figure 3). The system being settled to carry out 1D localization, it was possible to localize the detected events along the beam. Yet, in the case of the shear test, as main failure occurs at the edges where most of prestressing cables are not linear (Figure 1), it was decided to develop the existing system to realize a 2D localization of the events.

This was done in (Thobie, 2016) and relied on a hyperbolic triangulation taking into account the anisotropy of the structure caused by the inclination of prestressing steel wires. The precision of the method was assessed through pre-test calibration investigations to be around 16 cm.

Some acoustic events were detected during first shear loading phase. It actually corresponded to a concrete crack propagation induce by a poor mechanical link between the top flange and the rest of the beam. Such a detection seems surprising as it is often too low energy to be detected using such a system. Additional shear reinforcement was applied before the realization of the final shear test to avoid this unexpected damage mode.

The detected events during the shear test have been localized in Figure 9. A similar work to the one carried out in the case of the flexure test was done here. The events 1, 2, 3, 4 and 7 proved to have too low propagation speed to be attributed to prestressing steel wire failure. They may be attributed to flexural composite peeling-off in flexure or high energy fretting. Events 6, 8, 9 and 10 may be attributed to prestressing steel wire failure. They are all localized in the same area (cable 19).

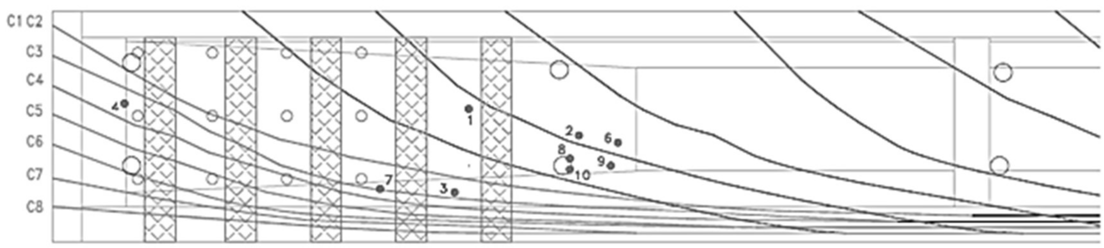


Figure 9. 2D localization of acoustic events during shear test up to failure

5 CONCLUSIONS

Though additional investigations are currently still under progress to validate the made observations or to compare the results obtained from different measurement systems, this article aimed at highlighting the main information gathered from acoustic monitoring during the different mechanical tests that were realized on a real-scale prestressed concrete beam coming from a real bridge and therefore in realistic ageing conditions. Acoustic techniques proved to be complementary with other monitoring techniques. Two different systems were used to get interest in specific locations (localized acoustic emission) or on the overall beam behavior during the test (CASC system).

The localized acoustic emission allowed checking the activation of existing cracks during the different phases of the flexural test and is one of the most adapted techniques for such an issue. It also allowed studying the edge zone during the shear test to propose a damage scheme of the beam.

The CASC system allowed to localize in 1D the most energetic events and a specific methodology was used to match the event with a physical phenomenon (mainly prestressing steel wire failure). It allowed proposing a damage process in flexure that matched well with the other measurement. In shear, the obtained results are still under study and it was observed that the acoustic events may not be only attributed in that case to prestressing steel wire failures.

Some additional investigations are under progress taking into account additional exploitation methodologies proposed in (Grosse et al., 2008) and (Nair et al., 2010). In addition, the results will be soon compared with modeling under progress and with the results of an autopsy of the beam led by hydro demolition.

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