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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 (localized acoustic emission and overall acoustic survey). A specific development will then be presented aiming at optimizing the obtained acoustic phenomena localization taking into account the anisotropy of the prestressed concrete beam. Finally, main results will then be presented for both flexure and shear tests.

1 General introduction on “CLERVAL” project

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 [1-2]

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 tested beam

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 (Figure 1). 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 2).



Fig. 1. Photo of the studied beam

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The prestressing system is STUP 12 Phi5. 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 [3].

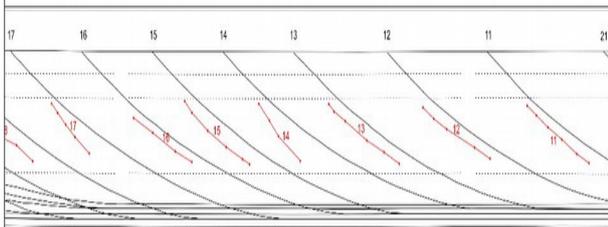


Fig. 2. Scheme of the prestressing cables position on one side of the beam

1.2 Test program

In order to obtain a maximum of information from the realized investigations, the test program was divided in several steps. A specific test platform was developed so that all the steps may be carried out on the same location (Figure 3).



Fig. 3. Test platform used for the whole program

First steps were dedicated to the study of flexural reinforcement (using adhesively bonded pultruded composite lamellas: 50 x 1.2 mm², 165 GPa) (Figure 4) 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.

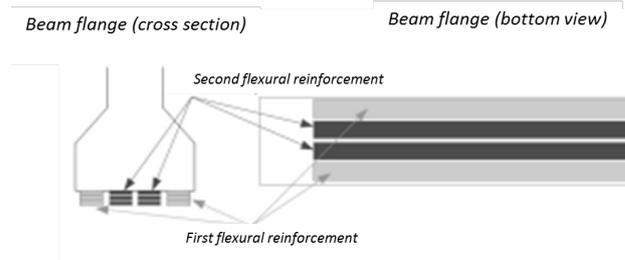


Fig. 4. Scheme of the flexural reinforcement applied on the beam flange

Second steps were realized on third of the beam and dedicated to the study of shear reinforcement in 3-point bending configuration (span: 9.7 m, and force applied at 1.5 m from support). The reinforcement implied the application of adhesively bonded carbon sheets: five 150mm-wide U-sheets with a spacing around 300 mm, and one specific horizontal edge reinforcement for the support area (105 GPa). Due to lack of space and to the geometry, the use of localized meshing for the anchorage was adopted (Figure 5). The experimental program 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.

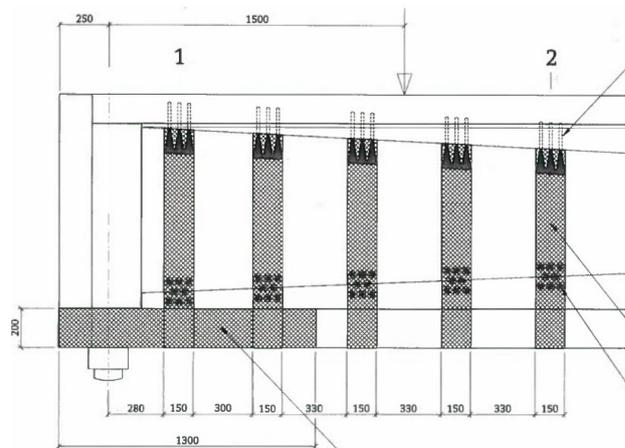


Fig. 5. Scheme of the shear reinforcement applied closed to the loaded end of the beam

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

Two different acoustic systems were used during the campaign. The first is called « overall acoustic survey » and aims at investigating the overall beam behavior. The second one is called « localized acoustic emission » and aims at studying specific areas on the studied structure.

2.1 Overall acoustic survey

The overall acoustic system was applied for each test up to failure and 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 [4] and is commercialized by A3IP (CASC system). 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 it was decided that three sensors should detect the phenomenon before obtaining an acoustic event.

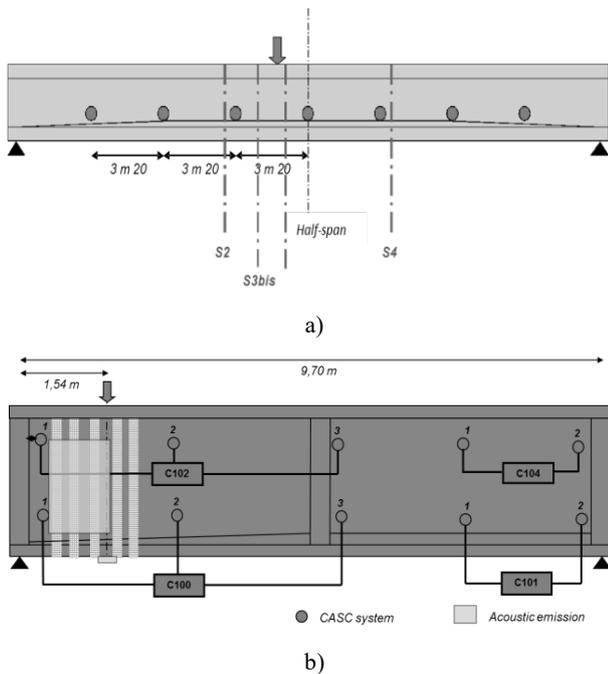


Fig. 6. Disposal of CASC sensors along the beam for flexure test (a) and shear test (b)

The maximum distance between sensors was fixed on site at 3.5 m based on preliminary investigations. Seven sensors were used in the case of the flexural test on a single line (Figure 6 a). This allows 1D localization of acoustic events. Ten sensors were used in the case of the shear test along two lines (Figure 6 b). 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 2). All the sensors were fixed to the beam using a low melting point material.

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. It is also possible to synchronize the data with an external signal. This was carried out using the applied load in our case. 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 from previous experimental campaigns in [5] and [6].

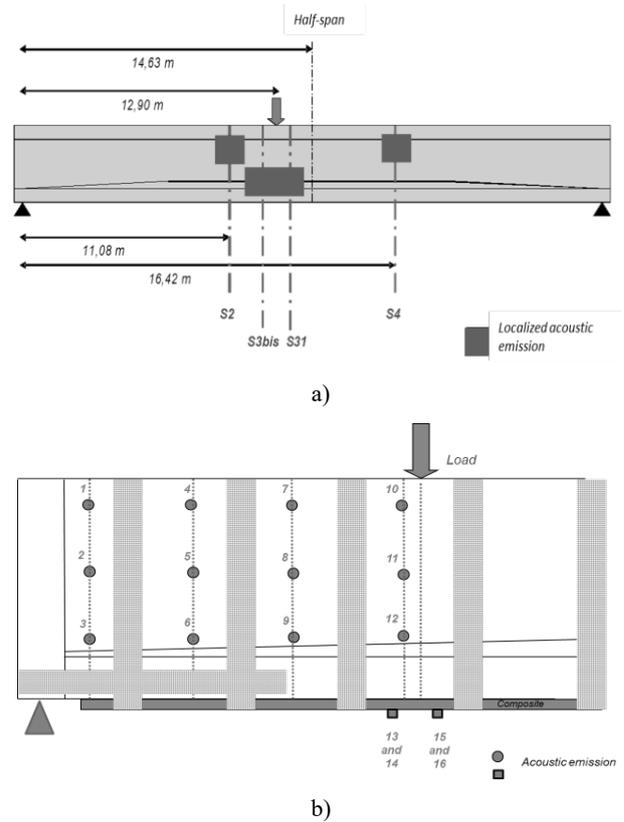


Fig. 7. Disposal of localized acoustic emission sensors for flexure test (a) and shear test (b)

In the case of the flexure test, three locations were more particularly studied: sections S2 and S4 above areas where cracks were identified prior to the experiment, and section S3/S31 which is located in the center of the beam (Figure 7 a).

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 positioning the sensors between the CFRP sheets on one face of the beam and on the bottom flange right under the applied load (Figure 7 b). Similarly to the first system, the sensors were all fixed to the beam using a low melting point material.

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 on figure 7a). 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 (Figure 8 a) was similar to the visual crack identification made after the initial flexural test (Figure 8 b). Sensors correspond to the green circles and acoustic to the dotted points. A red line materializes the crack.

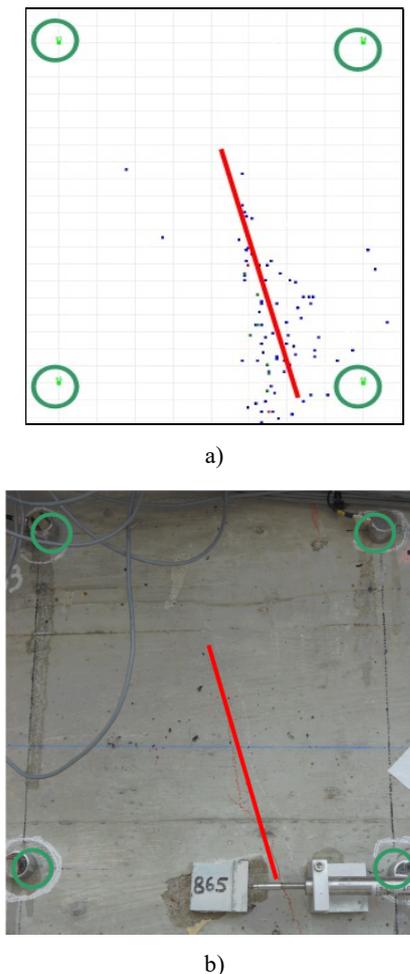


Fig. 8. Comparison of 2D events-localization (a) with visual crack identification at S4 section during initial tests (b)

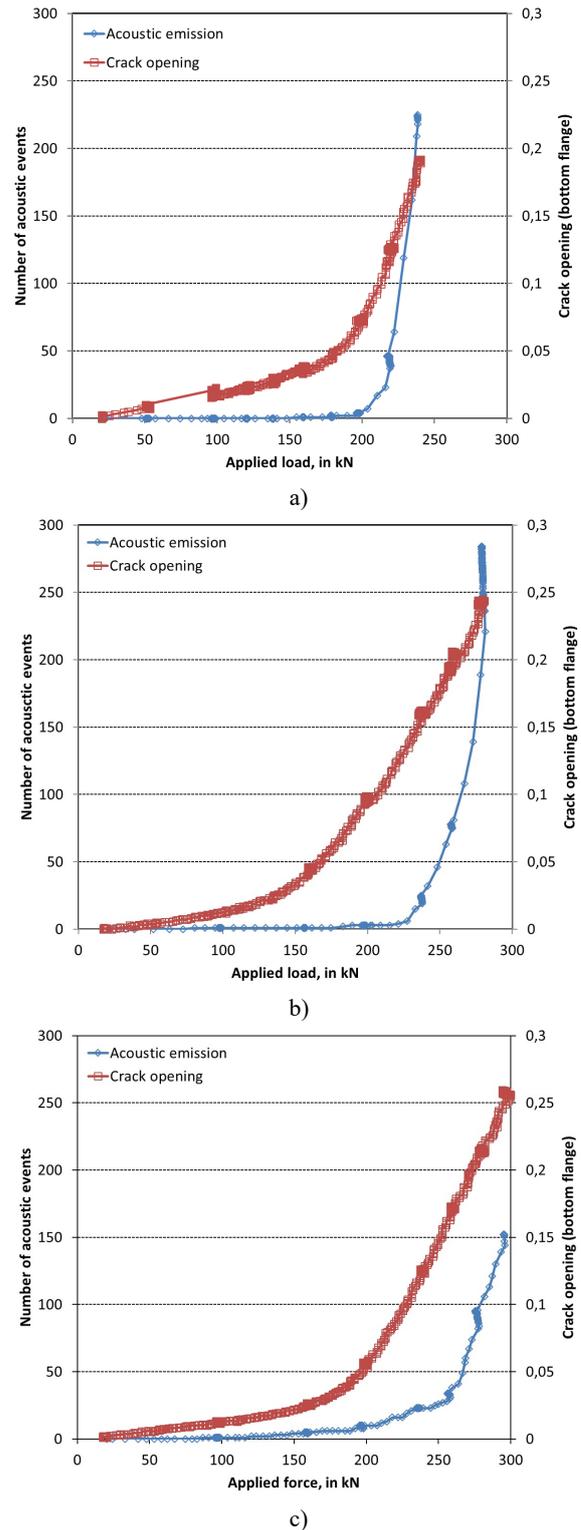


Fig. 9. Number of acoustic events and measured crack opening in function of the applied force before reinforcement (a), after first flexural reinforcement (b) and after final flexural reinforcement (c) at S4

Besides, for the three flexural phases, acoustic emission data was compared with crack opening measures made at the bottom flange (Figure 9). 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. Consequently, the slope modification point

of crack opening does not always occur at the same point than the start of acoustic emission. Both measurements may thus give complementary information on the state of the structure. It can also be seen that the reinforcement seems to have slightly delayed the onset of crack propagation. Acoustic emission technique is thus 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.

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 (Figure 10). 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 [7] to determine events corresponding to one prestressing steel wire failure, several prestressing steel wires failure and a bunch of prestressing steel wire failures. Most important events are given in Table 1. The average measured acceleration value is obtained from the average of the maximum amplitude of the three first sensors that detect the event. The average wave speed is determined from the position of these three sensors and the time when the threshold is exceeded.

Table 1. List of most important detected acoustic events using the overall acoustic survey system during the flexure test up to ultimate load

Event	Load, in kN	Average acceleration value, in g	Average wave speed, in m/s
1	400	10.7	4033
2	450	13	3675
4	460	12.9	3596
6	470	7.8	5751
7	-	11.7	5024
8	480	15.6	5400
9	-	13.8	5720
10	-	20	3846
11	-	7.5	4573
12	490	9	3519
13	500	9.7	3596
14	-	11.5	5688
15	510	16.6	3503
16	520	6.4	2154
17	530	7.6	2325
19	560	24.3	4454
20	580	7.5	5740
21	590	16.3	3895
22	610	9.3	5140
23	610	17.9	5339



a)



b)

Fig. 10. Photos of the beam after the flexure test (overall beam: a; detail on failure closed to the load application: b)

All the 1D localized events (Table 1) with the corresponding energy have been reported on the beam profile on figure 11:

- 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. This was correlated with crack measurements made in section S4.
- Then, several prestressing steel wires broke before the final failure that occurred at 615 kN closed to section S2 (Figure 10 b) (composite peeling-off). This was correlated with strain measurements made on one of the prestressing cables.
- From this moment, the applied force continued decreasing while the applied mid-span displacement increased. Numerous acoustic events occurred during this last step.

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.

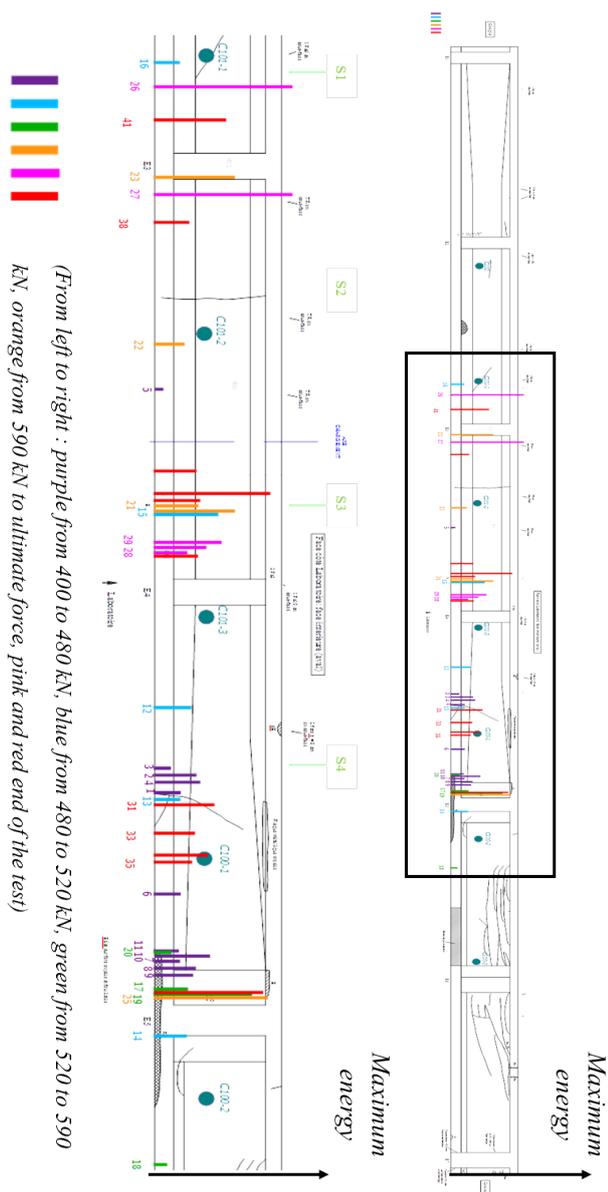


Fig. 11. 1D acoustic events along the beam during flexure test

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 realized on a part at the edge that has been little damaged and where no major acoustic event had been detected.

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

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 up to failure (Figure 12 and 13).

Three main periods were determined studying acoustic emission localization (Figure 14):

- 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 (Figure 14 a);
- 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 (Figure 14 b);
- From 1900 kN to the ultimate capacity (1970 kN), the acoustic emission was again localized under the applied load (Figure 14 c). At failure, a main inclined crack was observed from the applied load to the bottom flange out of the monitored zone using the localized device (Figure 12 and 13).



Fig. 12. Photo of the beam after the shear test up to failure



Fig. 13. Photo of the tested beam at the end of the shear test – detail of the main crack

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. No particular acoustic

emission could be revealed under the bonded carbon sheets though high mechanical stresses have been measured on them using strain gages. Unexpectedly, the final crack occurred outside of the monitored area using the localized acoustic emission system (Figure 12).

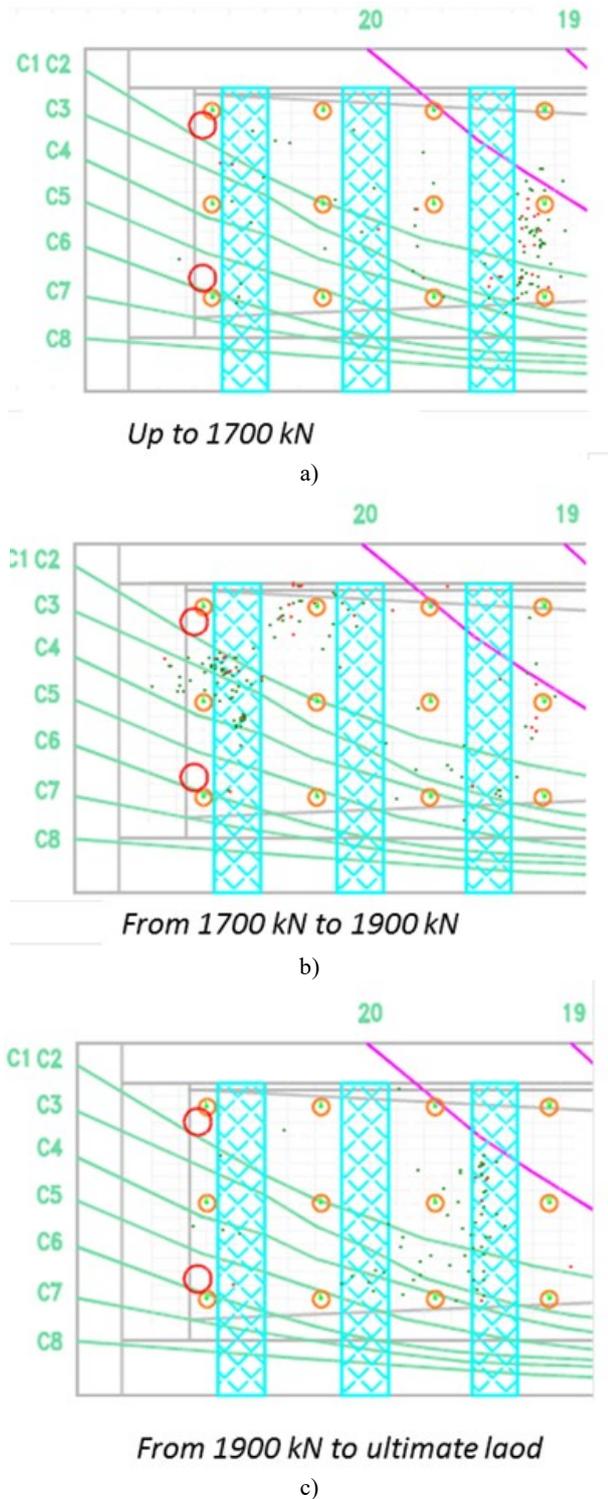


Fig. 14. Localized acoustic emission events during shear test up to failure (carbon sheets and prestressing cables are visualized) before 1 700 kN (a); between 1 700 and 1 900 kN (b) and from 1 900 kN to 1 970 kN corresponding to the ultimate load (c)

4.2 Identification of the failure process using overall acoustic survey

In the case of the shear test, two lines of five sensors have been disposed along the beam (Figure 6 b). 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 2), it was decided to develop the existing system to realize a 2D localization of the events.

This was done in [8] 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 induced 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 final shear test after CFRP reinforcement have been localized on the beam in 2D in Figure 14. A similar work to the one carried out in the case of the flexure test was done here for each of the detected events (Table 2) and adopting the proposed methodology in [7] based on the measured parameters (number of sensors detecting the event, wave speed, maximum amplitude).. 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 closed to the final crack: Figures 12 and 15).

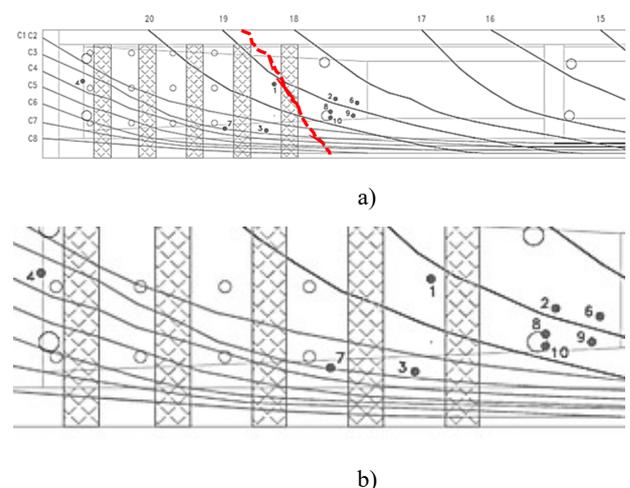


Fig. 15. 2D localization of acoustic events during shear test up to failure (whole beam with final crack: a; zoom on the events: b)

Table 2. List of most important detected acoustic events using the overall acoustic survey system during the shear test

Event	Load, in kN	Average acceleration value, in g	Average wave speed, in m/s
1	1570	12	1346
2	1805	11.3	1949
3	1791	17.3	1435
4	1870	6.7	1949
6	1765	25.5	3085
7	1725	13.3	2049
8	1657	19.2	3896
9	1626	10.3	3806
10	1597	13.1	6756

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 the case of flexure test 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, a 2D localization methodology was developed and allowed identifying the cables where failures occurred. 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 [9] and [10]. In addition, the results have been compared with modeling, and with the results of an autopsy of the beam led by hydro demolition. Good correlation has been determined though more failures were observed during the autopsy as the beam was led up to large damage.

The results may allow determining acoustic parameters that should be used during structure survey. They also allow checking some of the literature criteria regarding damage identification.

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