Non destructive testing of the Cleuson-Dixence Shaft

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Abstract
The special context of the rehabilitation of the Cleuson-Dixence pressure shaft brought the owner to have a specific approach in building this steel penstock. Unusual material and welding specifications and unusual care for safety could not come without unusual control specifications. Non destructive testing consisted of 100% visual, magnetoscopic and ultrasonic testing of all the welds. The determination of the NDT requirements was related to the qualification program performed for the material and welding.
A first choice was to provide two independent controls of all the welds, one supported by the contractor and one by the owner. It was also decided to have two different UT methods (automated and manual) for the two controls.
The second choice was to require recordable and reproducible ultrasonic controls, including the use of TOFD method. The two NDT companies proposed two different solutions to reach the requirements, one based on TOFD and pulse echo methods, the other based on TOFD and phased array methods, both runned by a mechanized system.
The third choice was to perform a qualification program of the NDT process. Specific validations of the systems on test blocs and real pieces as well as a validation of each operator were required.
For the first time, a complete automated ultrasonic testing was used on a large scale for penstocks works. A comparison of the performances of automated and manual controls was done. This experience opens the way to think differently the controls in our future works.

Introduction
The rehabilitation of the Cleuson Dixence penstock was ordered after an accident. The context is more precisely detailed described in another paper (O. Chène).
The expertises identified that the failure of the penstock was initiated on an existing crack created during the fabrication in 1998, which slowly grew between 1998 and 2000, when its brutal extension caused the burst of the penstock. A complete control of all the welds including MT and UT was done during fabrication. After one year of operation, in 1999/2000, a new control of all the welds was executed and defects were repaired. No indication was detected on the zone of the accident by these two controls. The crack was a surface breaking longitudinal crack, perpendicular to the surface on the concreted side. Its initial size was estimated to 200 mm long by 15 mm deep. It was through-thickness (37 mm) and nearly 280 mm long when it burst.
Such a defect should not have been missed. In that context, the owners required special specifications for the rehabilitation, including the controls.

NDT requirements
The non destructive testing (NDT) for the new shaft consisted of 100% visual (VT), magnetoscopic (MT) and ultrasonic (UT) testing and 5% radiographic testing (RT). It concerned all the welds: workshop, prefabrication (site workshop) and site welds of the shaft and of all elements subjected to pressure (like manholes).
The solution to ensure the high level of quality of NDT required by the owners hold in three main requirements:

- Two independent levels of controls
- Specific UT requirements
- A qualification program

The specifications for all the steps of the project were established with a global approach. It means that the specification for NDT was made in coherence with the ones for the conception, for the steel plates, for the welding, for the quality, for the organisation…

Fracture mechanics calculations were used to assess the critical crack size. This size depends namely on the material properties and on the design but must take into account the limits of the detection of the NDT method. A compromise was found between material and NDT requirements to make sure that critical defects cannot be missed by NDT without requiring too high material specifications. In parallel, investigations were carried out to evaluate the possibilities and the limits of the known NDT methods, their fields of application and their reliability. The discussion mainly dealt with UT methods for the detection of embedded defects.
As a result, requirements for VT, MT and RT remained within the usual EN standards, whereas requirements for UT were specific.
Two levels of controls

Two independent controls were executed. The first control (NDT 1) was part of the steel works contract, as usual. The second control (NDT 2) was subject of a contract between the owner and an independent company. It consisted in executing once again all the controls (VT, MT, UT) after the NDT 1 was finished and the result conform. NDT 2 was also in charge of rechecking all the RT films. Simultaneous work was not allowed and the communication between the two NDT companies was restricted to organization to ensure a total independence. It also permitted to compare the results of the two UT methods.

All the indications classified as non-conform by one of the two levels of control were repaired.

Requirements for the UT methods

A recordable and reproducible UT was required. The goal for the owner is to be able at any time in the life of the penstock to know if a defect has evolved, and assess its state to decide of the fitness for service of the penstock. Beside, during construction, the records make it possible for the owner to assess at any time the quality of the control works and of the welding works. This requirement implies to record the position in the weld with automated and mechanized systems.

One record is sufficient. It was decided that one level is made with automated UT (AUT) and the other with traditional manual UT (MUT).

The UT (both MUT and AUT) must detect all the defects longer than 10 mm and higher than 1.5 mm, independently of their orientation (transverse or longitudinal), their location (embedded, surface breaking on inner or outer surface) and their geometry (planar or not).

The use of TOFD method (Time Of Flight Diffraction) was required because of its good performances in detection (probability of detection and small size of the defects that are detected) and for its precision in the length and height measurement of the defects. But it could not reach alone all the requirements for it is weak for characterization and cannot give information (size or position) in the lateral direction. The solution had to be a mix of TOFD (diffraction) and pulse echo methods by reflection, but no specific requirements were given for this part.

Specifications used

VT was executed according to EN 970 with acceptance criteria according to EN ISO 5817 (class B) and CECT (class I table 3).

MT was executed according to EN 1291, with acceptance criteria according to EN 1291 (class 2X).

UT was executed according to EN 1714 level C. All the indications over the level of evaluation (-10 dB) were characterized according to EN 1713, length for step 3 (procedure cascade) being 10 mm. Acceptance criteria respected EN 1712 method 1 level 2 for volumetric defects. Non volumetric defects were not acceptable.

UT-TOFD was executed according EN 583-1 to 4 and 6 (with amendments) and CEN/TS 14751 (with amendments).

Acceptance criteria respected prEN 15614 level 1 table 2 with a maximum length of the non volumetric defects of 10 mm. Characterization was always done by MUT if AUT was not able to do it.

Reference blocs were conform to EN 583-2 (hole diameter 1.5 mm) for pulse echo and conform to XP CEN/TS 14751 for TOFD (hole diameter 1.5 mm).

RT was executed according to EN 1435 class B with acceptance criteria according to EN 12517-1 (class 1).

Description of the systems and procedures

In fabrication and prefabrication (site workshops), NDT 1 was done by Qualitech (Switzerland) and Applus-RTD (Netherland) as subcontractors of AMC (the consortium Andritz Hydro and MCE in charge of the steel works). They used an AUT 1 system combining TOFD and pulse echo with single angle probes. NDT 2 was provided by WPK (Austria) by MUT in fabrication, and by Atest (Switzerland) by MUT using phased-arrays probes in prefabrication. The control was done in workshop conditions with access from both sides, the pipe installed on rollers beads. It was X-bevels welded with submerged arc welding.

In the shaft, the site welds were executed by GTAW-HW, SMAW or FCAW on V-bevels with backing strips. The control was possible only from inside the shaft, in the slope, on platforms. NDT 1 was provided by the contractor (MCE) with MUT. NDT 2 was provided by Atest, with an AUT 2 system using TOFD and phased arrays methods.

To respect all the requirements, the AUT 1 system used 1 or 2 pairs of TOFD probes (depending on the thickness), and a set of usual pulse echo probes (single angle) to cover root, cap and volume and creeping waves for surface defects on each side. Transverse defects were controlled with 2 pairs of pulse echo tandem probes. The A-scan signal of each pulse echo probes was treated by the electronic system to provide a mapping (C- / D-scans). All these probes were fixed on a runner including the coupling system (with water). The runner was moved by a robot on a rail installed with suction and magnet grip along the weld. The curvature of the runner could be adapted to longitudinal and circumferential welds. The position of each probe had to be adapted to the thickness of the plate. The control was done in one run from inside the pipe. The
The AUT 2 system had a different configuration. It used only multi-element phased-array probes, one pair of 48 elements and an additional pair of 16 elements probes for high thicknesses.

In the phased array method, each element of the probe behaves like an independent single probe with variable angle. The electronic system can apply spatial and temporal rules on the angles of all the elements. The possibilities of rules are infinite (scan, focalization…) and make this method very powerful.

In our case, the probes provided the 1 (or 2) TOFD beams and 2 phased array beams with variable angle to cover the upper and the lower zones. Mixing diffraction and reflection in the same phased array probe was original. Transverse defects were controlled by another pair of phased array probes of 48 elements each.

The mechanical system was similar to AUT 1, using welding robots moving on rails. The control was executed in two runs, the one for longitudinal defects, the other for transverse defects with two runners including the coupling system (with water). The runners were more compact and lighter than the one of the NDT 1 system. It was a real advantage in site conditions were access is difficult and systems must not be fragile. The electronic part was also carried on site to do the interpretation immediately.

**Qualification program**

The NDT companies were subjected to qualification tests to prove their ability to detect, measure and characterize correctly the indications. The AUT and MUT procedures, the AUT systems and the AUT and MUT operators were subjected to a blind test on two qualification blocs with artificial flat defects (min. 1.5x10 mm) provided by the client. The blocs contained nine and eleven defects representative of all the types of defects to detect (position, size and orientation).

The AUT systems were also tested on the test tube (see article from O. Chène) to show their ability to execute a control on site conditions (in the slope, with scaffolding) before the beginning of the works.

Two pieces with real defects, obtained in the real conditions of fabrication were provided later by the client to test the AUT and MUT processes of NDT 1 and NDT 2. This test showed that the response of controls on real and artificial defects is different. AUT and MUT give always a good response with machined flat defects, but the answer to a real crack (same size and position) show important variations in size or amplitude. In further projects a special care will be taken to test methods on real defects. The advantage of mixing methods (TOFD, phased arrays, pulse echo…) is obvious.
Our UT requirements being unusual, the NDT companies had to develop new procedures, new systems and to adapt the execution to our standards. This required iterative modifications of the systems. The unusual (higher) specifications required also a learning period of the operators, especially for MUT controllers who are used to a standard method.

**Comparison of the AUT methods**

Each method presents advantages and weaknesses but was able to fulfil our requirements. Combining different methods increases the quality of the control. The AUT systems used are a real improvement for quality and for later inspections. These controls need higher investments than usual MUT because an AUT system must be developed for a given configuration, but execution is faster. An AUT file (phased array or not) contains more information than a MUT report which just gives the minimum data of the recorded indications. Phased array systems are powerful, flexible and compact. AUT software propose many tools to treat and show these data (Fig. 4, 5). However, the storage of the files and of the software requires a special and continuous care to be able to read the files in tens of years. No warranty can be given for the future. The human factor is still the weakest point in controls, but a recheck of the files can be done anywhere anytime. Another problem is that today controllers that can run an AUT system are still sparse.

The two AUT systems were reliable and efficient. The one developed by Atest had never been used in such a configuration and moreover was able to work successfully in difficult site conditions.

**Comparison of the two levels of controls**

The two levels of control were done with different methods, procedures and companies. NDT 2 could detect non-conform indications. Some were not seen by NDT 1: in those cases, these defects existed and were missed due to human factor. Some others had been recorded by NDT 1 as conform: those cases of disagreement concerned indications on the limit of the acceptance criteria (length or type). Discrepancies were observed between MUT 1 and MUT 2 who had different probes (20x22 mm and 8x9 mm probes) and different procedures to fulfil the same requirements. It induced unnecessary discussions for minor defects. As the official characterization method was the manual one, no problem was observed between AUT and MUT.

To solve the problem NDT 1, NDT 2, CDC and the engineer (the consortium EDF - Stucky - Bonnard et Gardel) agreed on a common MUT procedure.

**Conclusion**

The quality of a steel work depends mainly on the quality of the welding. But the NDT is highly important to ensure that it was done properly.

The special specifications chosen for this project ensured a high safety of the scheme. However, unusual specifications should only be required for unusual cases.

The AUT methods developed have become our new standard for controls of complete penstock, both for workshop and site welding.