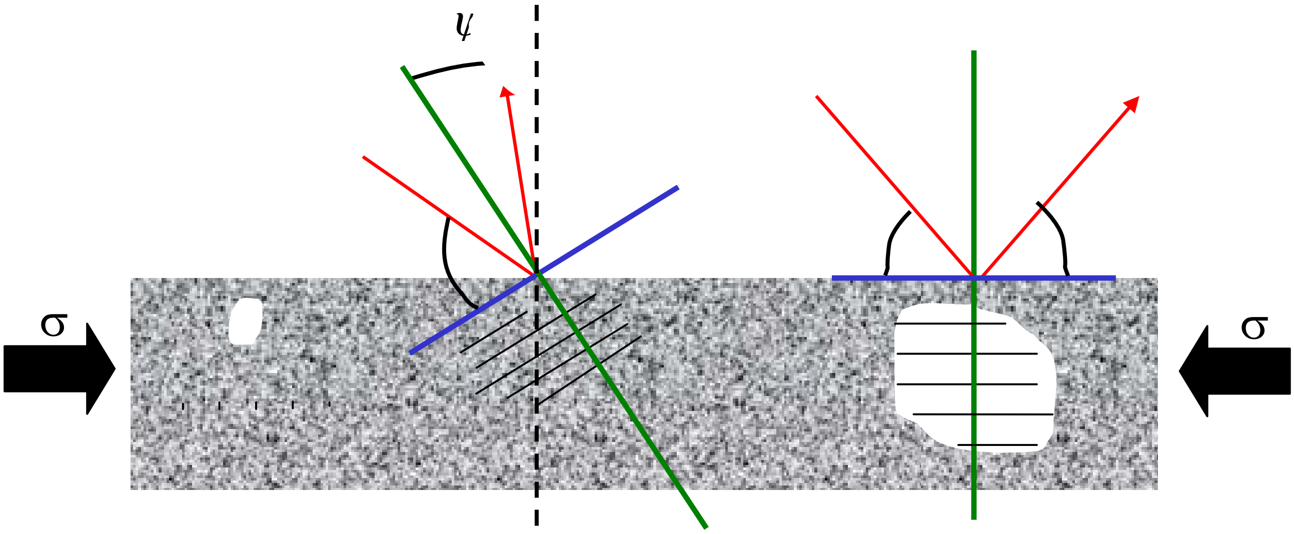
FIXED AND PORTABLE X-RAY DIFFRACTION

Summary

Residual stress measurement using X-ray diffraction can offer many advantages in comparison with other known techniques. In fact, the use of portable diffractormeters and in some cases, it can be considered a non-destructive technique and used as production control.
In this work we introduce two main diffractometer types for the analysis of residual stress and the use of XRD in several applications.

Fixed and portable diffractometers schemes

Considering that the main principle for the XRD measurement of the residual stress is the displacement of 2θ angle (the diffraction angle) with the observation angle Ψ (see figure below), it is necessary to point out as follow.



In a “fixed” diffractometer the sample is moved in rotation along ψ (Figure1), while in the portable diffractometer is the goniometric head itself which rotates around this angle.

Figure 1- Fixed X-Ray diffractometer

The next drawing shows another fixed diffractometer in which an open "Eulerian cradle" can be seen, in which the sample to analyze is mounted.

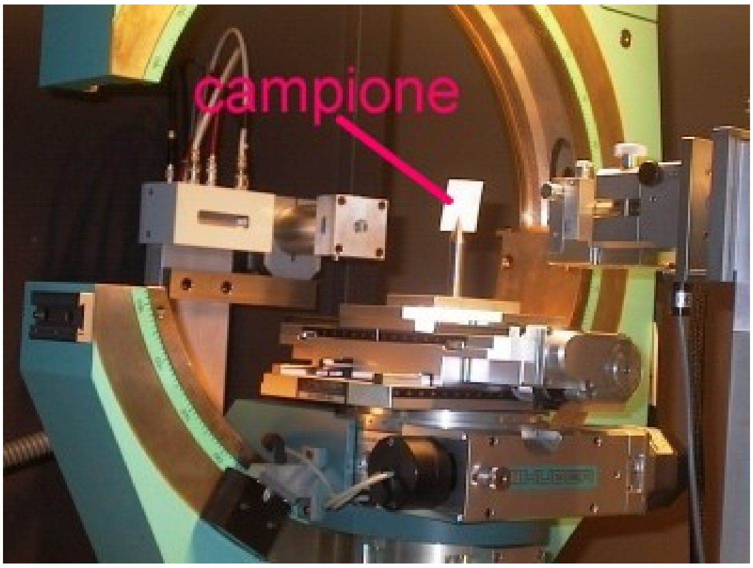


Figure 2 -RX Diffractometer with an open Eulerian cradle

It's quite evident that fixed diffractometer is indicated when one needs to analyze easy geometry and small dimension samples in order not to change the diffractometer structure.
Portable diffractometer scheme is presented in the next drawings; we show two equipments with different detectors, one with a scintillation counter and the other with a position sensitive linear detector (PSD).

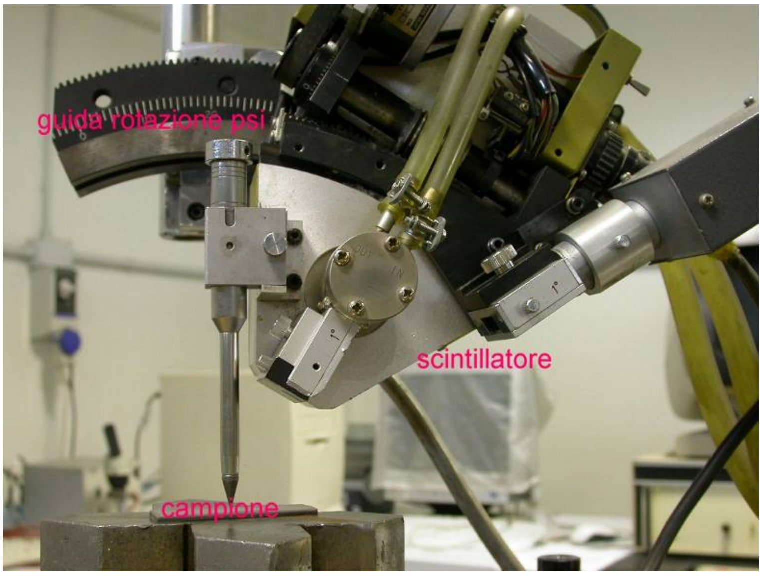


Figure 3 - Portable diffractometer with scintillation counter

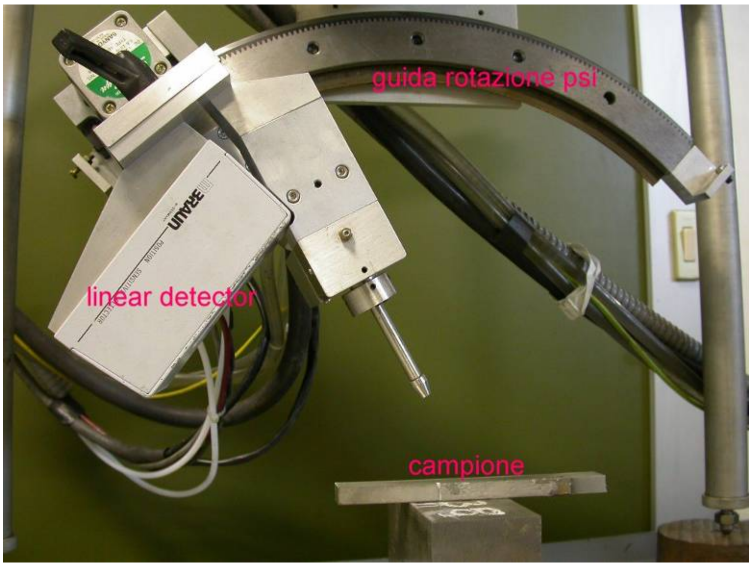


Figure 4 - Portable diffractometer with PSD

Thanks to the fact that in these portable systems the sample is not mounted on the diffractometer itself, there are no dimension, weight and – in many cases – shape limits in the measurement of residual stress of samples.

XRD applications in automotive field

One of the main sectors in which residual stress is requested and used is the automotive field, especially on transmission shafts gears, where the shot penning process is commonly used. This technique is basically a small steel spheres bombing on the sample surface; part of the kinetic energy of the spheres is transformed in plastic deformation and this determines compressive stresses which improves the resistance to the fatigue of the material. Thus is strictly important the precise knowledge of the compression induced with the treatment, in order to check the process during the production. The main Automotive Producer have already prepared their specifics, which define the minimum requirements of the stresses, mentioning specifically the XRD stress analysis. For this reason, specific diffractometers for residual stress analysis of automotive gears has been produced. (see next figure).

Figure 5 – X-ray diffractometer equipped for the analysis of automotive gears

In order to realize the analysis at required depths, an electrochemical removal of the surface is needed: this technique does not introduce variations in the original stress status. In addition, the analysis of teeth's flank can be done only cutting the gear, so the methodology became destructive. On next drawings you can find some photographs showing different steps of the measurement and a typical result of these tests.

Figure 6 – Gears to analyze

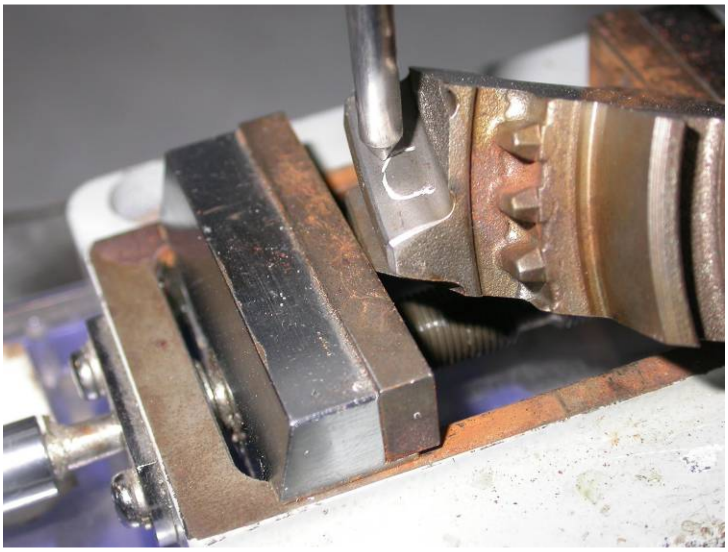


Figure 7 – The sample after the cutting and area of investigation

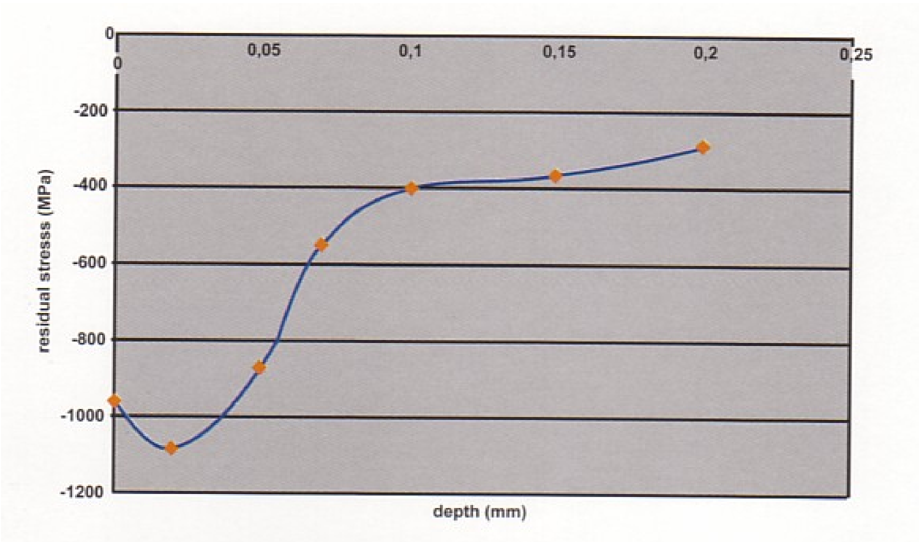


Figure 8 – Residual stress profile on a flank of a shot-peened tooth

In the same automotive field, residual stress are considered of strategical importance in the analysis of all the movable parts of the engine: live axles, pistons and rods. In this field (excluding F1), there are no specifics concerning the requested residual stress, usually the stress measurement is done to find and fulfill the trouble' research. On live axles even the portable XRD can have some difficulties, considering the sample's shapes, in order to take measurements on some specific spots not easily reachable. Sometime a section of the axle is needed, and the test became destructive.

For process control, as for example tensions brought by grinding pistons pin or connecting rods, to be tested in reachable spots, the diffractometer technique is absolutely non destructive (next drawings). Using XRD one of the main Formula 1 team succeed optimizing parameters of nitridation and the following grinding, inducing great compressive stresses which bring to a great improvement of the fatigue's resistance of the sample. Now the same team is also verifying the stability of the process measuring the stress on pin-rod of the whole manufactured driving shafts.

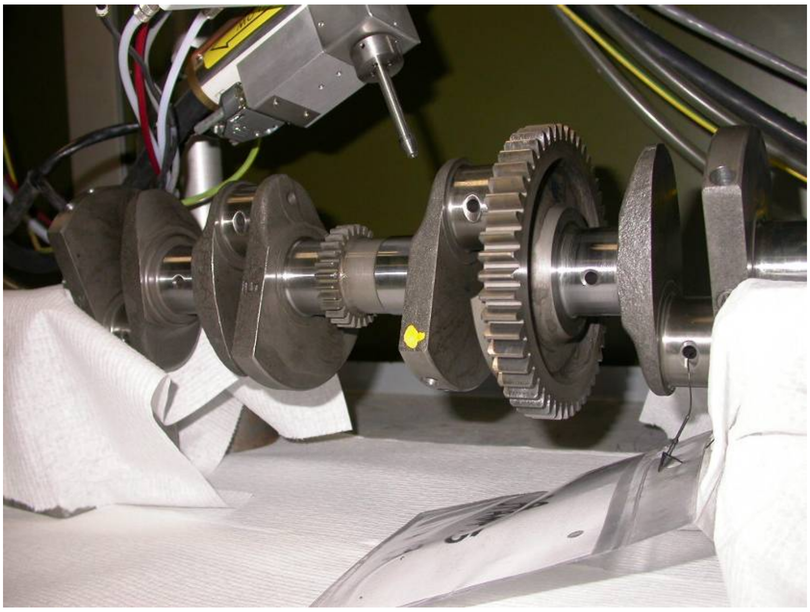


Figure 9 – XRD stress analysis on a part of an engine

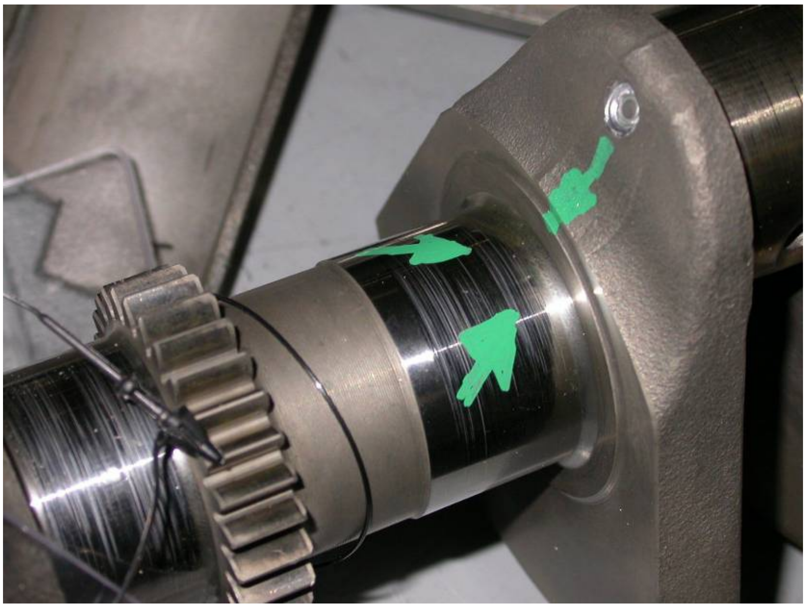


Figure 10 – Zone of analysis

Talking about team engines sector, it is also very useful the information about the residual stress present on shoot-pinned and grinded rods, the grinding polishing process is done in order to reduce the roughness induced from shoot-peening treatment, which also increase the resistance to the fatigue. In order not to introduce tensile stresses which can be dangerous, it is absolutely important that the polishing treatment is done using well defined parameters. XRD is the only non-destructive technique suitable for this goal. Residual stress values fall between -400 MPa and -500 MPa, according to the materials used and shoot-peening and polishing treatment parameters implemented.

Figure 11 – Connecting rods after shot peening and grinding

Other components that can be analyzed thanks to XRD stress are light-alloy rims, both mass production and racing team, due to the fact that these are elements subject to fatigue and consequently conditioned by existing residual stress. XRD also in this case can present some handy problems due to the most stressed zone, usually located inside the same rim (next picture).

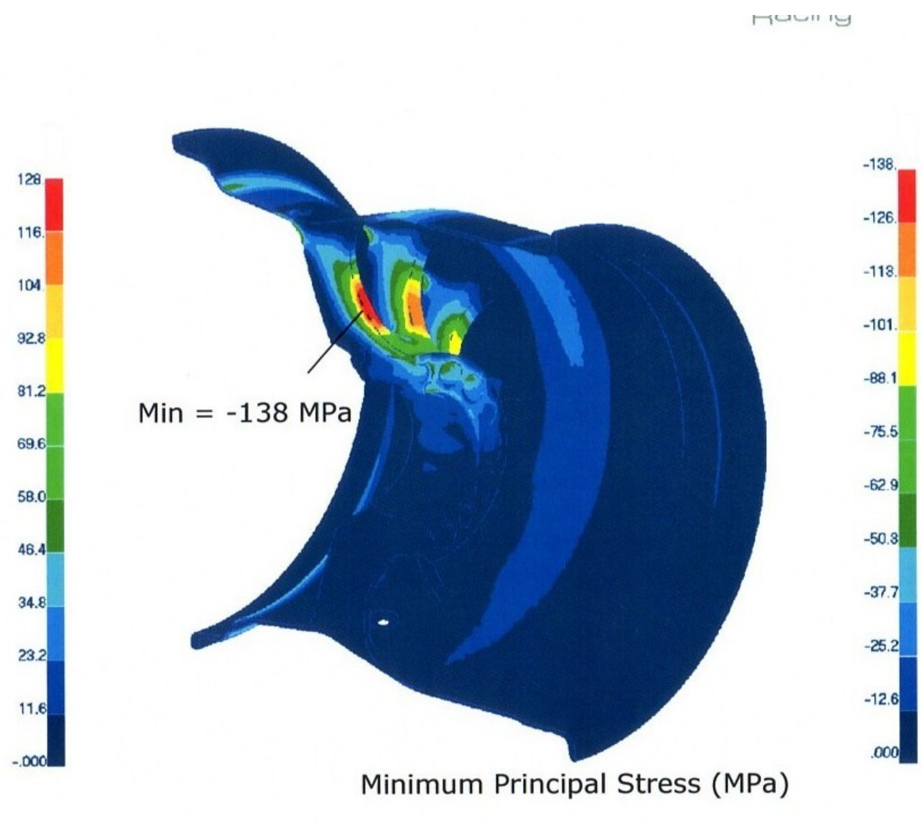
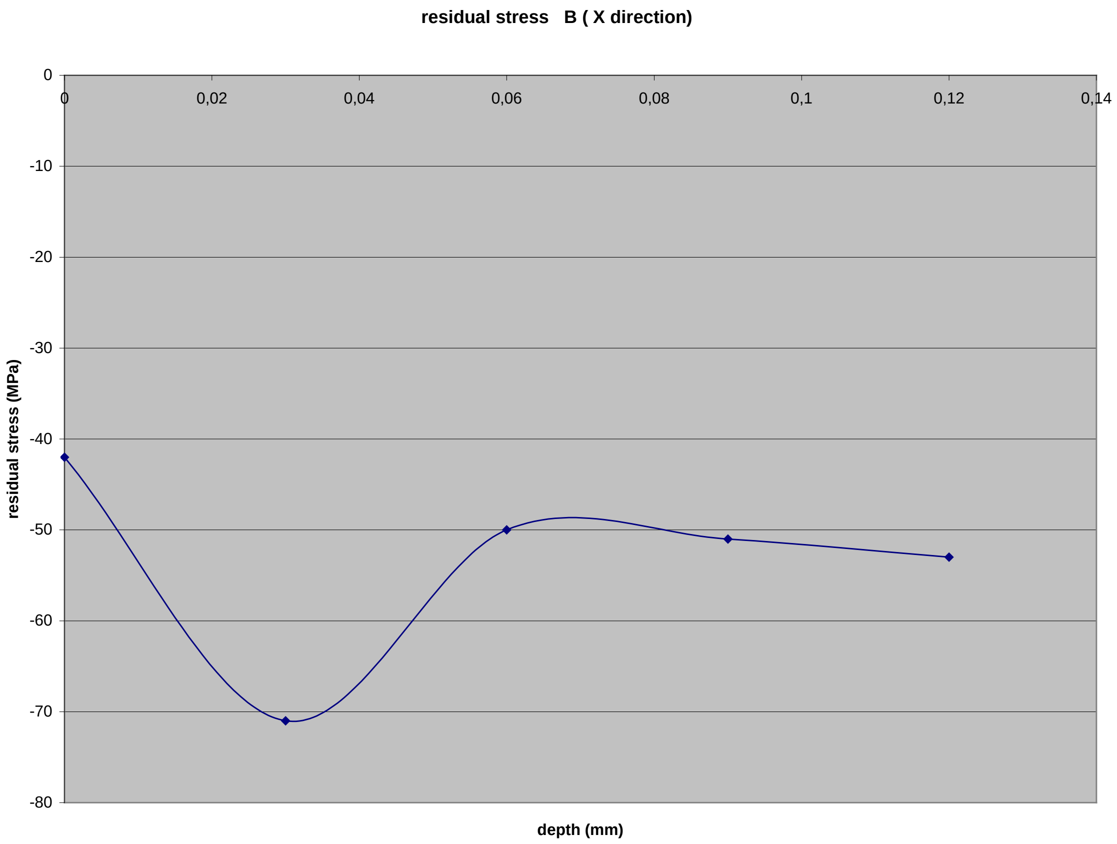


Figure 12 - FEM analysis of the stresses on a F1 rim

Induced stress analysis, on the most stressed spots, by forgings and mechanical treatments on a F1 Magnesium alloy rim, has required a sectioning of the sample; the results obtained are shown on the following picture.



From the drawing it comes obvious the importance of the mechanical treatment (milling), which modifies the preexisting stresses for a depth of approximately 0.06 mm.

Figure 13 - XRD stress analysis on a F1 rim.

XRD applications in energy production field

Residual stress analyses are also important for those components of an energy turbine subjected to fatigue; in this case portable diffractometers that work in situ can grant a very valuable support. Usually gas turbine' compressor blade are shoot-peened on the root area and thus it is strictly important to really know the characteristics of the induced stress state. Usually the analysis of these spots does not present particular complexity but electro chemical removal process to reach the needed depth.

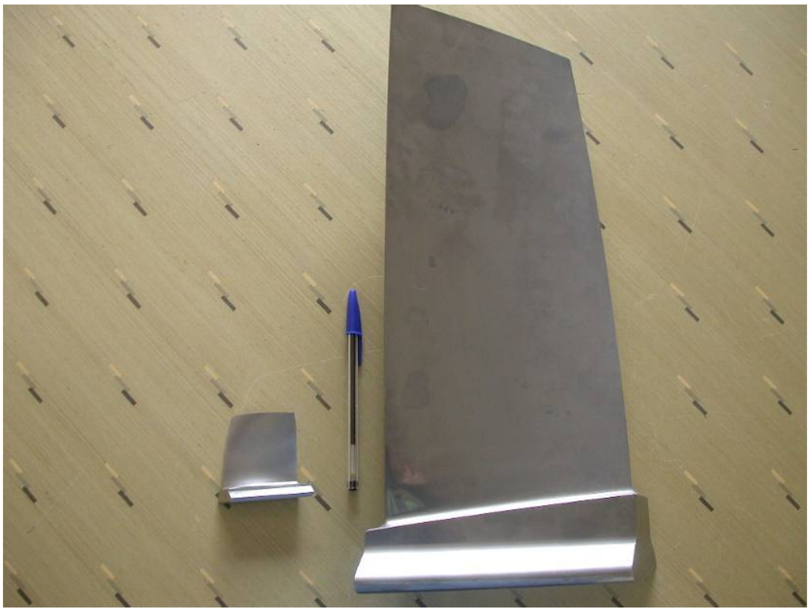


Figure 14 – Gas turbine blades

From our XRD analysis, we can notice that the induced stress resulting from shoot peening process is influenced by the thickness of the blade, and it decreases for smaller thickness. This allows one to optimize the shoot-peening parameters according to different blade shapes, bringing to a better gain on fatigue resistance.
In the following table we show results coming from two blades of different dimensions (and also thickness) subject to a shoot-peening process of identical parameters.

Depht [mm]	Residual stress [MPa] little blade	Residual stress [MPa] big blade
0.00	-410+/-15	-733+/-27
0.03	-303+/-13	-745+/-23
0.06	-308+/-13	-777+/-21
0.09	-353+/-13	-523+/-19
0.12	-52+/-15	-492+/-16

Turbine blades of the last stages of a steam turbine have been also analysed with XRD, in order to verify the validity of mechanical finishing process on root and the profile (Figure 15). In the next table we show the values measured on the profile as a function of the mechanical finishing process selected.

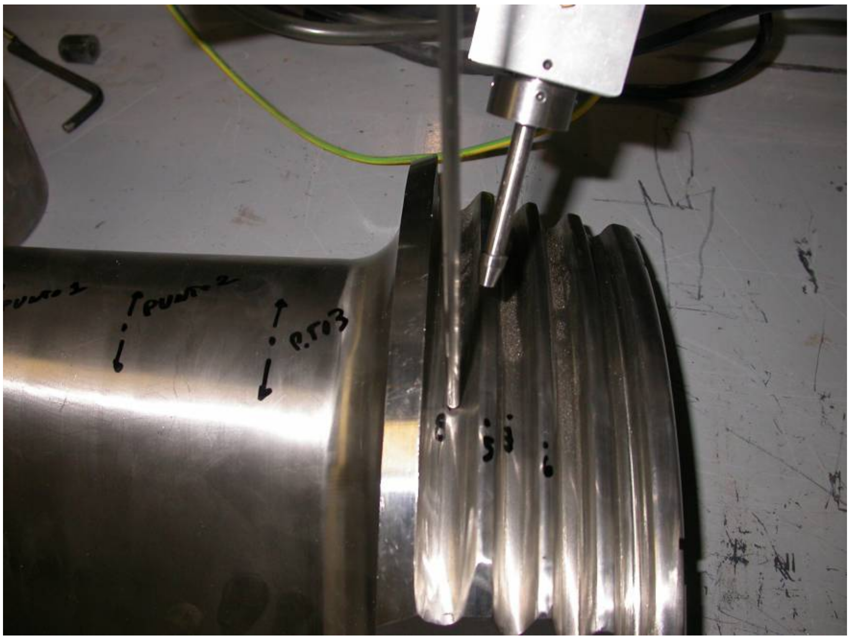


Figure 15

depht [mm]	Residual stress (MPa) GR180 finishing	Residual stress (MPa) GR600 finishing
0.00	-259+/-19	-210+/-15
0.04	-26+/-11	+59+/-12
0.10	-46+/-12	+12+/-8

Slightly more complicated is the residual stress analysis on Pelton turbine wheels, due to shapes and weights (sometimes more than 10000 kg!); we need to draw on the "portability" of the equipment and build an appropriate frame to support the placing of the portable diffractometer (see following pictures).

Figure 16 - Portable diffractometer mounted on a Pelton wheel

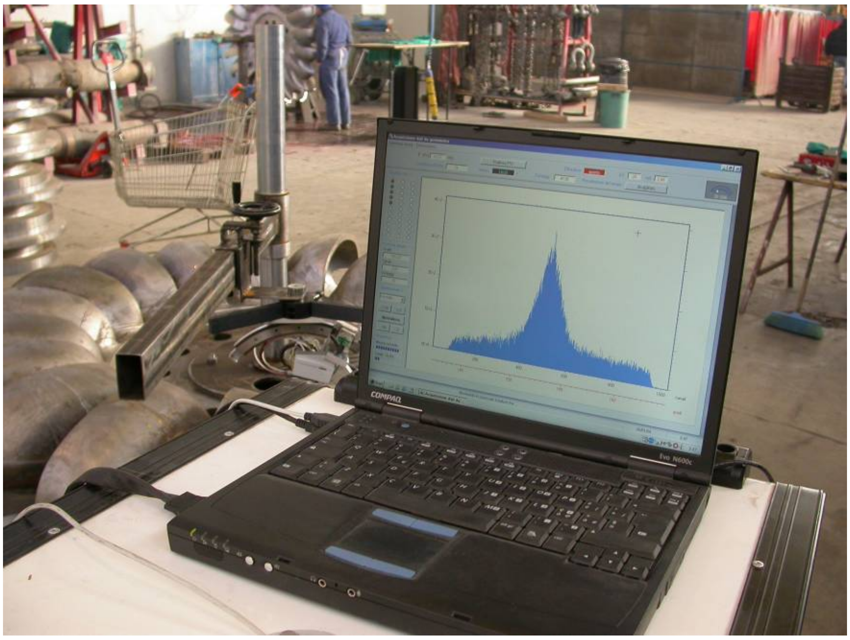


Figure 17- XRD in field

Unfortunately XRD cannot give information about the most stressed region of Pelton wheel, because it cannot be reached (next picture) and obviously the sample cannot be cut!

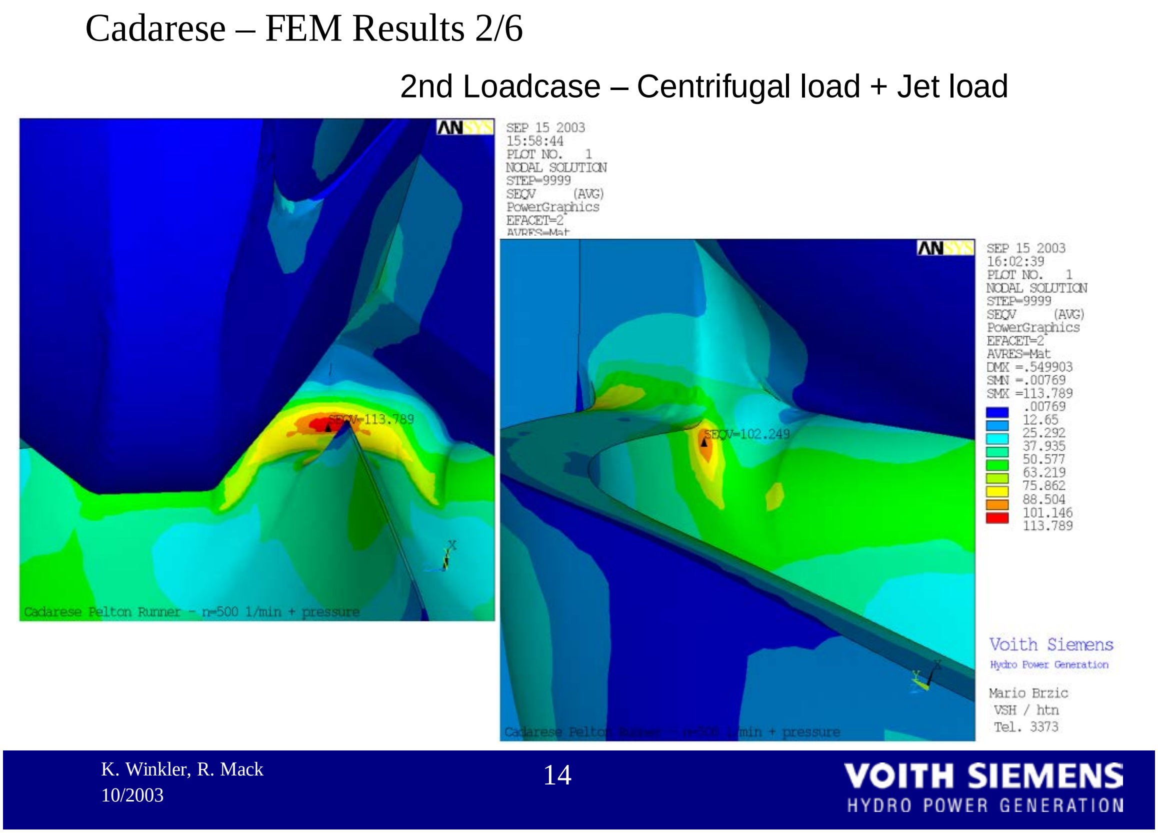


Figure 18 - FEM analysis of the stresses applied to the blades of a Pelton wheel

Remaining in the hydroelectric field, residual stress measurements acting on a working rotating Kaplan shaft, subject to torsion (inducing a permanent deformation) have been released (See Figure 19).

Figure 19 – In situ XRD analysis on a Kaplan wheel shaft

The differences between residual stresses values measured along directions placed at 45° and 135° on shaft axis are due to the action of the torque that has produced stresses which values, on the surface, were higher than the limit of proportionality, i.e. in the plastic field. This has determined, when the torque was removed, a residual deformation well taken by the diffractometer.

XRD applications on welded structures

Residual stress measurements coming from welding processes are of particular importance. Infact the possible introduction of induced tensile stresses can produce cracks during the working of the structure. Also in this case it's important to place the diffractometer directly on the structure; only in this way we can analyse the real stresses due to the welding process. (Figure 20).

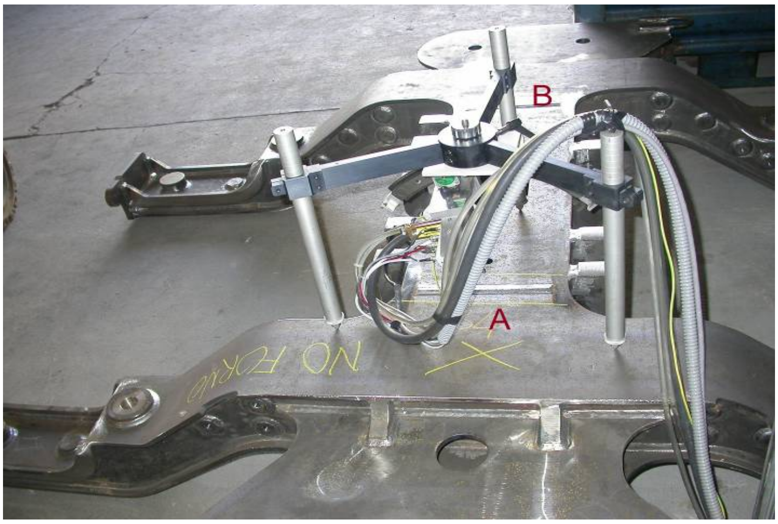


Figure 20 – The Ital Structures diffractometer mounted on a railway frame

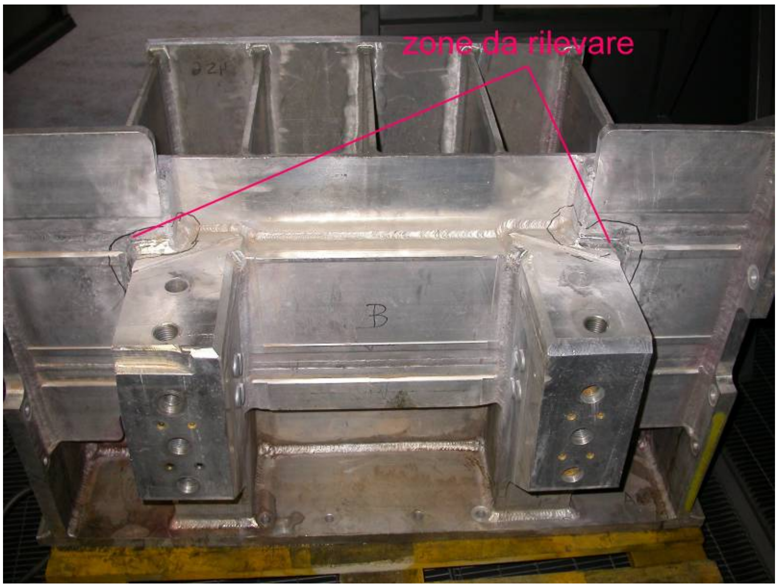
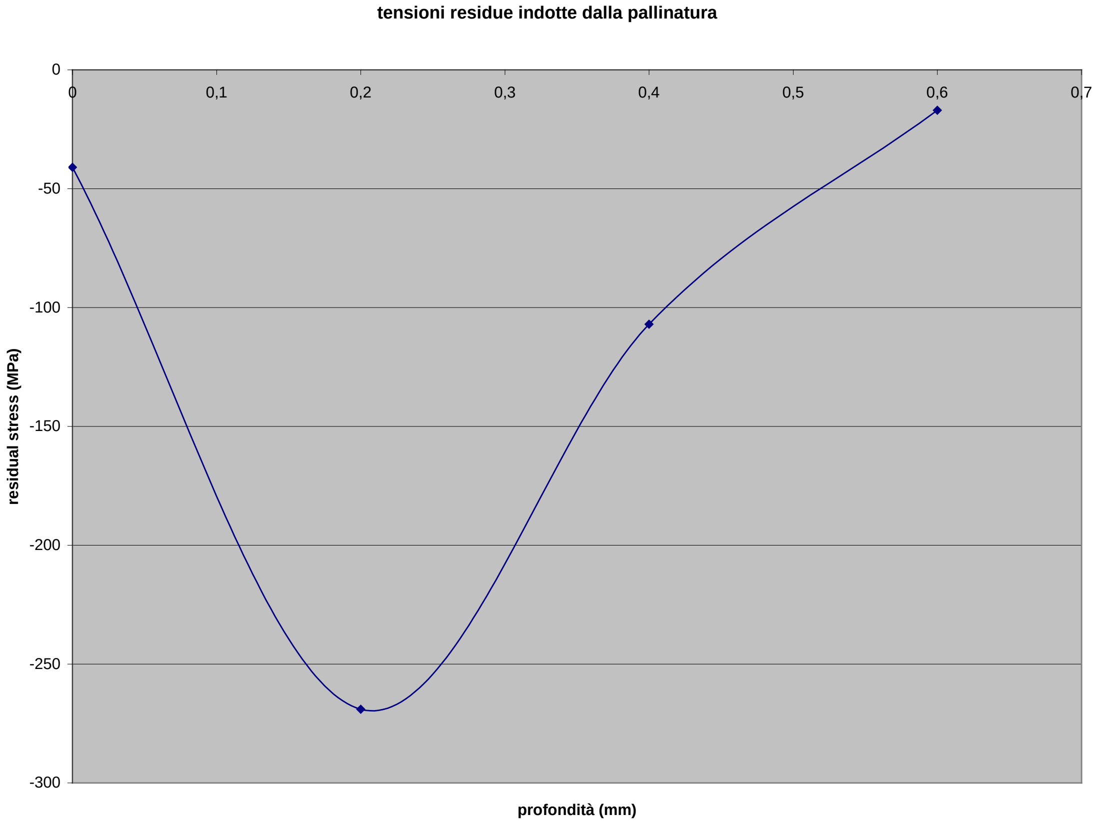


Figure 21 – A particular of an aluminum railway structure

Figure 21 shows a welded aluminium railway frame. In order to increase the resistance to the fatigue, a controlled shoot peening on nearby welded areas was made; after this process the residual stress analysis has been done.
The obtained results shown on next drawing.



Due to the fact that the residual stress technique is a non-destructive one, it was possible to expose the same components to fatigue tests.

XRD applications on big structures

Rarely people talk about residual stress on big public structures and more difficult that the measurements are being asked. An exception is the residual stress analysis of an historical interest steel bridge (Figure 22); the goal is to evaluate the remaining life of the structure and understand which structural refurbishment and reconstruction operations are needed.

Figure 22 – The "Ponte Longo" on Giudecca Island (Venice)

Due to the fact that the frame of the bridge was heavily attacked by corrosion, it was necessary to electrochemically clean the surface in order to take measurements.

Figure 23 – Original condition of a surface to analyse

It was also necessary to build a structure just to take care of the diffractometer system and take the analysis (Figure 24).

Figure 24 – The hanging diffractometer

Analysis taken nearby one rivet's hole grant the following results.

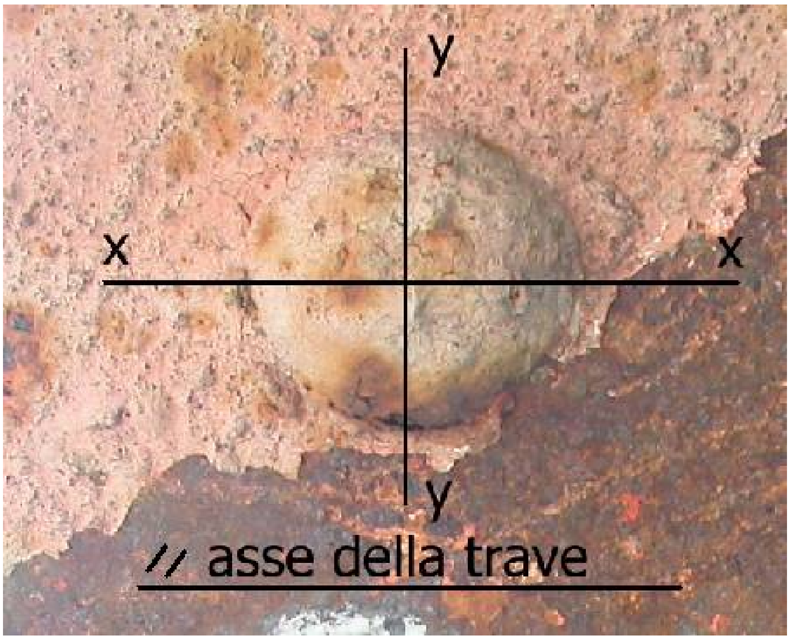
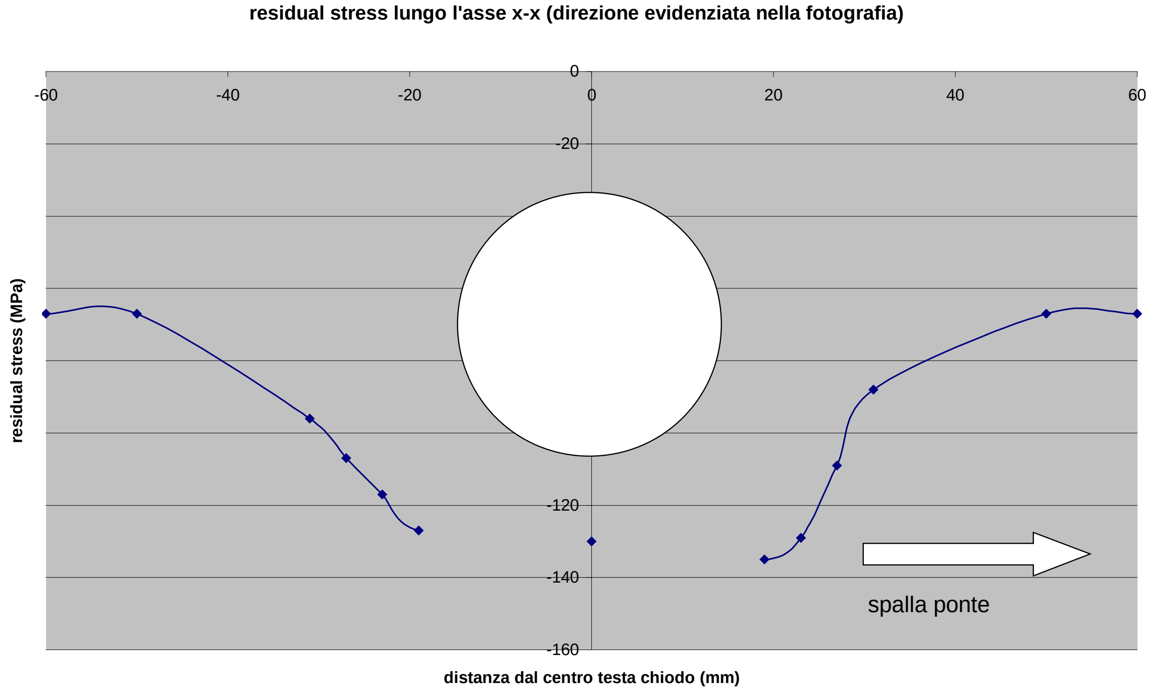
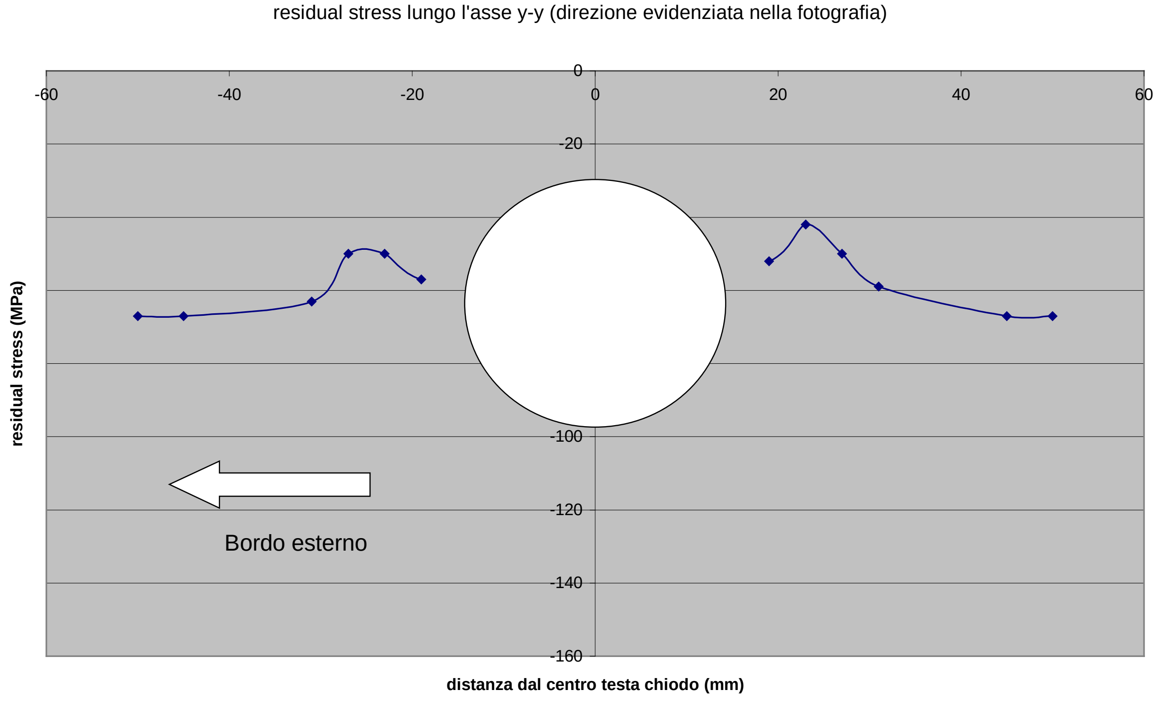


Figure 25 – Reference axes used





Another XRD application is the stress determination on arch rods of a masonry structure in Salò (Italy), with a significative historical value, seriously damaged by an earthquake (next Figures).

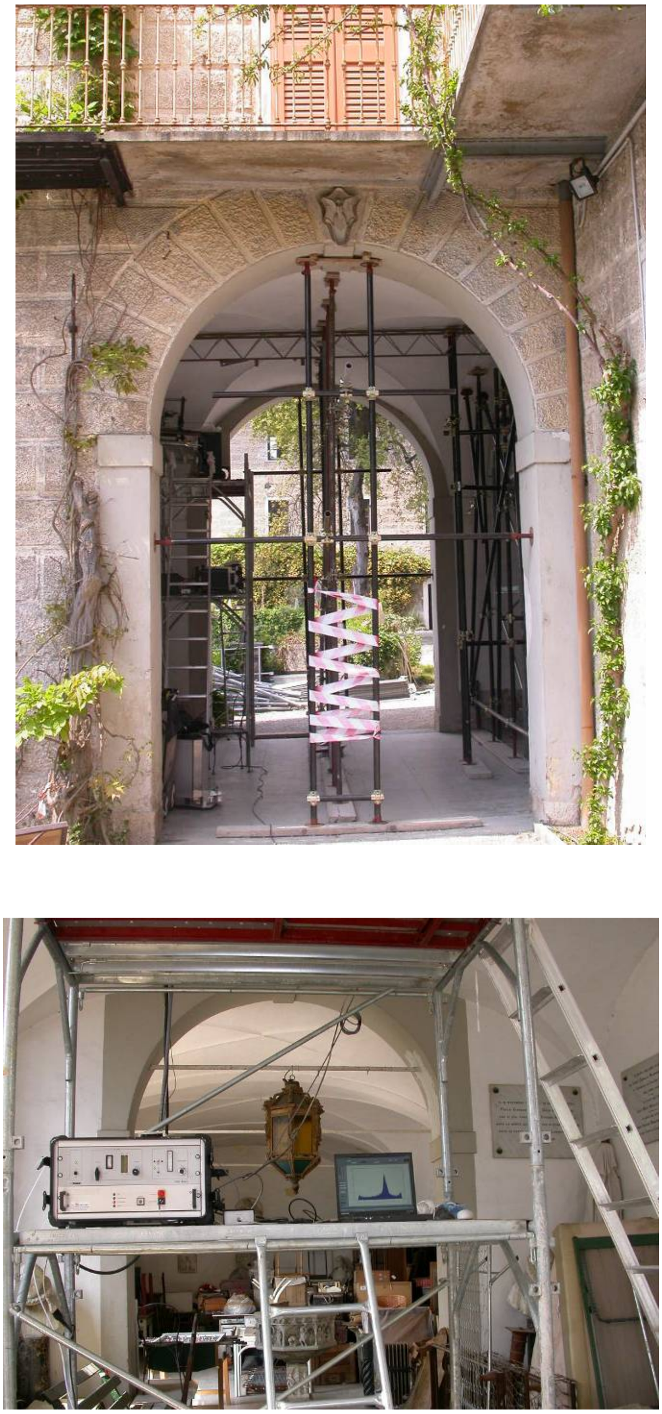


Figure 26 - XRD stress analysis on tension rods

Even in this case an electrochemical process was necessary to bring on surface the rod steel. Results coming from the analyses allowed the evaluation of the effective stress acting on the rods and as a consequence to to evaluate the real behavior of the eartquake damaged arches.

Information:

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