A point of View about
Diagnostic Investigation for Metallic Tie-rods between History and Innovation

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Abstract
Earthquake is a natural phenomenon, which creates lakes and mountains, and, although it cannot be anticipated, yet it can be foreseen, in terms of expression of a behavior documented by a seismic history of a site and through technological development of its ancient architecture, stratified on that area. Under this point of view, topic of seismic prevention not only finds demonstration of its opportunity, behind its need, to be realized, in cultures able to live together it, but also sees its real putting into practice through application of lots strategies, characterizing mitigation seismic hazard.

Among these, there is the complex and not linear category of technological constructive measures, which in history were invented, improved, substituted, and in these a particular role is given, thanks its historical continuity and its simply efficacy, to wooden or metallic tie-rods, linear or locking, with wedge or turnbuck, preventive or repairing, visible or hided, able to constraint or to contain, caring or pre-stretched, but always aimed to realize an efficacious constraint because modulated to seismic action.

However, in a different manner for others applicative fields, as steel or reinforced concrete structures, on site diagnostic investigation topic, specifically directed to study qualitative characteristics of materials and mechanical quantitative behavior of tie-rods it does not present a law and procedural context, although new Italian and European seismic norms often recommends using tie-rods in repairing and as preventive technology. But at same time in topic of investigation about tie-rods does not exist a linear orientation, in terms of diagnostic methodologies, protocols and procedures and this situation defines a not coherent and sometimes constraint technologies-active and passive systems, microseismic recording, frequency methods, dynamic tests based on vibrating rope theory, static tests determining differential between theoretical and real deformation, only listing some well-known techniques.

If this condition shows an always needed ferment in academic and scientific community, at same time it puts ordinary technicians and professionals in difficulty to try orienting criteria in a context where of ten advantages and limits are not clean, above all in capability to be used in integrated methodologies able to permit a reciprocal validation of these methodologies.

For this reason, the paper, rather to explain a applicative case history, tries to purpose a short essay about this topic, providing to give some evaluating elements to project and to conduct an on site instrumental investigative campaign about metallic tie-rods, preliminary to intervention project and especially regarding historic buildings in seismic area.

Keywords: metallic tie-rods, on site diagnostics, seismic prevention

1. Introduction: a syntetic historic recostruction

A paper, which has as its object a homogeneous, but necessarily just hatched, description of state of the art on a very complex issue such as diagnostics applied to tie-rods cannot start without a historical introduction. This is because the structural diagnostics is today one of most innovative scientific research field and best skilled activity in professional practice, yet it is a science too widely and erroneously described as "contemporary," because born at same time as the Building Science and unknown to the world of Art of Constructive, as a kind to respond to a way of conceiving the building no more in terms of balance and not technique, but of resistance and materials. Hence the attempt to devote a brief introduction, through a description of some historic machines, ancient and complex genesis of methodologies and technologies still used today for tie-rod investigations [1-2].
A first interesting tool, used to check conservative condition and tension of cables and ropes, is designed by Leonardo da Vinci (1452-1519), it is a wheel, which can be locked with a joint between two teeth using a lever; this instrument, useful to prevent accidents while loading a crossbow or to avoid overturning of a wagon, is suggested by Leonardo also for periodic verification of conservative conditions of ropes or leather string of crossbows and bows, especially to check effectiveness of connections in frames, suggesting its use in case of very tight ropes and in case of vulnerability of attachment points, just as in the case of tie-rods of historical buildings (Fig. 1).

Another Leonardo’s tool is a tensional axis for cables, coming from a pulley, dismantled and then from time to time adaptable to different sizes and disk axis; on the opposite side are positioned some graves with known weight used to put in tension a rope and its respective pulley with a dynamic action, known, constant and variable from trial to trial; verification of deformation of disc or pulley is used to quantitatively assess its extent and possible flaws in its realization; this is an homologous test to many trials strength and toughness analysis of materials and structures, such as tensile tests for strands and metallic bars or such as pull-out tests for connections and welds (Fig. 2).

Other interesting instruments are designed by the metallurgist and inventor Vannoccio Biringuccio (1480-1539), which suggests a tension testing machine for wires and chains, so to define structural and behavioral characteristics of different metals (Fig. 3), or by Ulrich Bessnitzer (XV), which describes a tensioner for cables, which, through listening sound effect emitted by the vibrating string, could allow an evaluation of tension state stress of rope, in connection with its natural frequency ω.

This is today this same principle used for checking tension in metallic tie-rods of historic buildings, through the vast complex of non-destructive technologies, based on an evaluation of natural frequency (Fig. 4).

Another interesting machine is described by Jacques Besson (ca. 1530-1573), it is a complex device, powered by human force, used to do and test screws and threads. This machine consists of a lathe, which performs various types of threads, and of a track, opposed to the frame, which creates a sort of pull-out tests for understanding the coaction capacity and resilience (Fig. 5).

A complex machine is designed by Fausto Veranzio (1551-1617), it is a "machina funes torquens", able to weaves, predetermining their diameter, ropes, cords and metal cables; at same time this machine performs a sort of static tension test, which serves both to avoid twisting rope during productive phase and to check that there are not in the wires defects able to cause to weaken the rope (Fig. 6).
A strategic role in the diagnostics history for metallic tie-rods and bars in architecture must recognize to Giovanni Poleni (1683-1723), who in one of his best-known book, “Memorie istoriche della Gran Cupola del Tempio Vaticano, e de’ danni di essa e de’ ristoramenti loro”, describes some diagnostic tests, performed on materials making up the Vatican Dome (stones, bricks, mortar and steel bars), in order to value their physical and mechanical properties, above all in terms of fracture stress.

Others very interesting Poleni’s mechanical tests are realized in order to determine iron tension strength or for an assessment of effectiveness of retreading in the Dome and their eventual implementation, creating a “machina divulsorica” (Fig. 7), used by Poleni to claim that iron resistance, in cables, rods or bars, is certainly related to metallic alloy composing them, but a significant importance should be attributed also to metallurgic processing, leading to quantify behavioral depletion of materials, realized with a sort of extrusion technology, in comparison with made with hot deformation, especially about the warming phase for bars, before tightening, so as to determine a kind of pre-tension.

Contemporary studies are realized by Jean-Baptiste Rondelet (1743-1829) about some structural problems of pillars in the Panthéon in Paris, and their resulting consolidation; to this aim Rondelet devotes some emphasis on diagnostic tests, made to evaluate mechanical properties of materials, using a machine, not much different from a contemporary tension test machine, in order to determine what today we could define average reference characteristic value of metallic alloys used for bars applied to pillars in the Panthéon (Fig. 8).
2. Diagnostic methodologies for ancient metallic tie-rods

The diagnostic methodologies available today for metallic tie-rods, mainly iron, steel, cast iron and more, especially in historical context, are lots and sometimes, as mentioned earlier, they are a connection or evolution between different and ancient systems, thus making not exhaustive and not very useful a rigid typological distinction. However, the range of methods is so complex, that a macro categories classification can be useful, especially for ability to systematically explain advantages and limitations:

A. Laboratory

The destructive tests require a sample of metal tie-rod, sometimes with a significant alteration of their static and dynamic condition, especially in view of further diagnostic tests aimed to investigate this aspects; so in this context they are described only in a brief listing information [3] (Figs. 9, 10).

A.I. Chemical-physical

A.I.1. a Optic or laser spectroscopy: which, by recording light emissions of metals, provides information on composition of alloy for a tie-rod or its parts;

A.I.2. Nuclear magnetic resonance: it can detect presence of a forging defect, which can be not visible from the outside and could be determined by metallurgical and forging methods, typical of period of its realization;

A.I.3. Optical or laser microscopy: it allows an observation and evaluation of techniques, morphology and composition of investigated section, being particularly useful in evaluation of alloys in specifically zones, like in welding areas or for degraded portions, especially in case of delamination, corrosion, creep;

A.I.4. X-ray diffraction: it is an analytical technique, used for identification of constituents, particularly useful in the study of historical type ferrous alloys, because of their large variability;

A.I.5. X-ray fluorescence: a method of elementary type, rather fast and at same time precise, suitable for metallic materials, due to their high conductivity;

A.I.6. Photoluminescence/thermoluminescence: a technique borrowed from the dating study for ceramics and pottery, it is useful in study of tie-rod in order to assess presence of passivation or protection treatments or in case of tie-rods involved in fire.
A.II. Mechanical tests
The mechanical tests, although most useful in determining the structural behavioral characteristics, especially in terms of performance, however, unlike the chemical-physical investigations, usually require large portions of tie-rods, thus making very limited its application, above all for issues related to an irreversible alteration of original tension conditions.
However, they are useful for example when an ancient tie-rod is to be replaced with a new one, so it is possible to modulate the new tie-rod in according to characteristics defined in the old one, which, once removed, can easily be objects of mechanical tests, of course there is not capability to determine its tension state.

A.II.1. Traction: it is aimed at obtaining data about mechanical properties such as tensile strength or breaking strength and it is made by a dynamometric universal machine, normally equipped with a flight-data acquisition unit able to give output data using strength-deformation diagrams;

A.II.2. Bending: this test is used to determine the ductility of a sample of tie-rod, it is operated by a hydraulic iron bending machines with various angles of bending and variable cycles of bending and straightening, according to its alloy, so to expected fragility, and especially to radial section of tie-rod;

A.II.3. Pull-out: it is a pull-out test for samples of tie-rod appropriately bound in a concrete ballast; little applied to pre-industrial tie-rods, it is an interesting investigative test to assess technical quality of tightening tools for post-industrial plate anchors or to check effectiveness of new tie-rods. It can also be made on site, with appropriate hollow jacks, but in this case stress is usually limited to the elastic field;

A.II.4 Beam test: is a methodology able to determine adherence and attrition for tie-rod samples, appropriately bound in a concrete ballast. The applications are largely homologous to those described for pull-out test.

A.II.5 Hardness: it is used to determine hardness, ie resistance to penetration, which features metal alloy used for a tie-rod; the operational limit of this technology is usually made by the too little section of sample tie-rod;

A.II.6. Resilience: it is a dynamic mechanical testing, aims to quantify fragility of a sample tie-rod subjected to predetermined temperatures; it is particularly useful for tie-rods victims of fire, lightning or thermal shock.

A.II.7 Welding sections resistance: a dynamic mechanical test, sometimes cyclical, it is used to determine tearing resistance of a tie-rod in specific sections, for example welding sections, connections, hook, etc.

Figure 9 SEM image of a weld [3]                    Figure 10 Detail of a fracture surface [3]
B. On site
B.I. Static tests
B.I.1. Ultrasonic test: it is an in contact investigation, which, through piezoelectric transducers, determines time flight of an ultrasonic signal under a predetermined frequency; in metal tie-rods it allows to evaluate, with a good approximation, density $\rho$ and Young's modulus of its alloys, but also presence of micro-cracks, holes determined by welding defects, inclusions of fusion defects, etc.;
B.I.2. Magnetometry: it is a qualitative test, able to locate and define geometry of hidden metallic elements; in investigation of tie-rods is particularly useful for check portions of tie-rod allocated in sections of walls and not visible plate anchors;
B.I.3. Corrosion detection: it is an in contact portable equipment, operating with eddy current; it allows to evaluate thickness and geometry of a section in a tie-rod affected by oxidation, so as to provide information about reduction of effective resistant section which is usually lass large than the geometric nominal section;

B.II. Dynamic tests
B.II.1. Releasing test: it is a direct and non-destructive investigation, useful for tie-rods where there is a tensioner in sufficient use conditions or destructive investigation for tie-rods without connectors (Fig. 11); in fact it is necessary to loosen the tensioner or to cut the tie-rod moving away edges until to nullify tension in tie-rod. The determination of linear geometric translation of known points and knowledge of its elastic modulus will get to evaluate tension in the tie-rod. Limits of this investigation are not only in operating conditions posed in the introduction, but also to ensure that release of tie-rod does not cause structural problems, even more so considering suddenness of this operation; finally difficulties to restore original use conditions makes this methodology rarely use in favor of indirect methods, below described;
B.II.2. Vibrating string test: it is an indirect dynamic method (Fig. 12) useful to determine tension in a tie-rod in relation to measurement of its first vibration mode frequency, requiring a calculation model which neglects bending stiffness and therefore suitable only for long tie-rods with small section, highly strained. For this reason it is a useful methodology in case of ropes and strands, but it is rarely applicable for historical tie-rods, especially if lightly strained.
"Releasing test" and "vibrating string test" were the first experimental methods for determining tension in a tie-rod [4-5-6-7-8], and derive from them, but mostly only conceptually, more recent and sophisticated, although sometimes less versatile, methods, described below [9-10-11-12-13-14-15].

![Figure 11 Releasing test-scheme](image1)

![Figure 12 Vibrating string test, scheme](image2)

B.II.3. Laser vibrometry: to check structural damage, particularly on plates or spur anchors, useful especially after severe seismic events, when a tie-rods is severely called to fulfill its role. In this case, this methodology is particularly useful to highlight phenomena of delamination in steel characterized by very little sections. Limit of this technology lies in its
ability to provide data only on a portion in detail investigated, so as to require a long time to investigate a very long tie-rod, and in a lack of portable equipment to operate in uncomfortable conditions, such as those normally are present specifically in the investigation of tie-rods (height, need scaffolding, etc.);

B.II.4. Electronic sensors: this very large category includes tools designed to evaluate tension in a tie-rod by determining its oscillation frequency \( f \). This happens through documentation of acceleration in free oscillation of tie-rod under dynamic action, by piezoelectric accelerometer sensors and a data acquisition system, which typically consists of a modular multi-channel accelerometer unit (Fig. 13). This methodology is quite easy to apply, fast in terms of execution and its analytical analysis allows to define a mechanical stress-bending beam model, thus overcoming one of the main limitations of dynamic sensors, used a decade ago, that is an inability to take into account flexural rigidity of peculiar history tie-rods, because they generally are rods and not ropes. However all this large category of methods requires, during analytical phase, some approximations of calculation, such as:

- doing a not easy discretization of constraint conditions, imposed in model as flexible joints at both ends;
- modeling tie-rod as a single linear element, thus not taking into account elements are very common in ancient practical use, as a variation of section in tie-rod in its linear development, dictated by historical executive criteria, but also presence of suspended elements or welding, additions, tensioners, connections;
- finally need to predetermine density \( \rho \) and Young's modulus \( E \), which, specifically for historical tie-rods, can be significantly different even from point to point in the same tie-rod and which would need a deeper knowledge both in composition then in terms of metallurgical characterization, which usually only are determined by destructive investigations and therefore with need to have a sample.

An interesting variant of this methodology is called "modal analysis", it is realized always using a little instrumented hammer and acquisition of acceleration is determined by vibration modes. However, this methodology differs in its ability to detect the first four or even six frequency response and in possibility to impose in calculation model some refinement algorithms, intended to take into account variability of section of tie-rod, both in terms of shape and size, as well as to express possibility of predicting elastic constraints, in case of tie-rods where there is an inefficient or inadequate anchor or in case masonry has bad technical characteristics or finally in case of tie-rods are vulerated by dynamic events, obviously first of all by an earthquake.

B.II.5. Fiber optic sensors: a methodology specifically designed for monitoring investigation, which exploits ability of this technology to determine in an checked element its synchronized strength and deformation with great precision in its localization in each area of sensor, also parameterizing anomalies and defects, such as in welding sections, localized oxidations, creep (Fig. 14).

Moreover, possibility of setting up a smart texture, made by flexible fibers woven with linear strain sensing optic fibers, embedded in an epoxy matrix, allows accurate distributed measurements, particularly useful in linear elements, such as a tie-rod, also in order to evaluate homogeneous areas and particularly insidious portions (for example welded sections or connection in central areas or oxidized portions, particularly at its ends). Application of this smart texture, given its high performance, can also takes a reparative or supplementary role, at aim to allow even a non-continuous monitoring of its durability and effectiveness, especially in terms of adherence of texture to tie-rod.

Limits of this technology lie in: sensitivity of optical sensors, which are often not adapt to operative conditions of a construction site; a very high cost to perform tests especially in terms of monitoring; need to have discontinuities in section of investigated tie-rod, even if
very small (cracks, radial delamination, detachment caused by bed welding, etc.) and then an increase of stiffness of polymer used as an adhesive, which leads to inability of quantitative comparative analysis in case of a long-term monitoring.

Figure 13 Electric sensor

Figure 14 Fiber optic sensor

3. Diagnostic methodologies for new metallic tie-rods

Introduction of metal tie-rods is not a method which concerns only to the past, but it is a technology still today widely used in structural conservation and restoration and in this case there are lots technologies, in addition to those already described, useful above all to be used to monitor appropriateness of intervention and its implementation. While in fact the modern metallurgy can give for new materials with great precision cognitive data, for example density \( \rho \) and Young's modulus of elasticity, instead an very debated issue concerns capability of sophisticated determination of tension to give to new tie-rods, in particular to evaluate adequacy of efficacy of anchors, especially not in case of plate but spur anchors. In this sense, the best known technology is relating to combined measurement methods of strain gages for vibrating string testes, generally with an integrated thermistor, used not only for the first stretching of tie-rod, usually made step by step, but also as a monitoring procedure, in order to check for in range tension changes or unexpected performance.

The creation of new tie-rods also allows to project especially suited anchors for tension conditions to which it is expected their exercise and in according to quality of masonry; a proper functioning constraint in fact is essential for maintenance of tension conditions and especially in the case of seismic action, in order to avoid tearing the anchor from wall. For this aim, are now widely used various technologies related to load cells, very reliable when applied to plate anchors realized in suitable dimension and where it is possible to guarantee an optimal alignment between tie-rod and walls (Fig. 15). These conditions are not always achievable especially in historical context and this is the reason because a measurement of tension using load cells for historical tie-rods, where it is replaced only the anchor, often does not provide sufficiently useful data to correctly define tension to attribute to old tie-rod with new anchor plate.

Another interesting technology concerns smart FBG-based; there are fiber bragg grating strain sensors, with temperature compensator sensor and a miniaturized system of optical fiber sensors, for data transmission; they are projected to be integrated into tie-rod during its construction. Capability to place the equipment in different points in tie-rod allows a precise and discretized monitoring into sections (for example in correspondence of a sleeve or in the center) and it allows monitoring of an hypothetic change of tension in the tie-rod, under particular conditions, for example to understand variations and ranges of stress (Fig. 16). The
technology, borrowed from ropes and ropes for bridges and tensile structures, can also be
adapted for monitoring ancient tie-rods, of course cutting the tie-rod to accommodate the
smart FBG sensor, which, however, may not have sectional size less than 30mm, so it is not
often adapt in monitoring of small diameter tie-rods. Moreover, because it is necessary
cutting the tie-rod, this methodology is not able to determine undisturbed tension conditions,
but to monitor the new imposed conditions [16-17-18].

Figure 15 Piezoelectric load cells for anchor plates

Figure 16 Smart FBG sensor

4. Conclusions

The complex range of diagnostic tests available for study of metallic tie-rod, although
expresses a wealth of possibilities, at same time demonstrates how they are necessarily only
partial in their ability of determination of the most important data in a structural analysis, as
the conditions of constraint of tension, but they are still quite inaccurate in capacity to value
distinctive features, such as efficiency of tensioners, or behavior due to dynamic stress, such
as an earthquake, of tie-rods with constraint above all if these are variable dissipative or
passive hysteretic, today more and more used also in restoration, because they are particularly
suitable for solution of articulated structural problems concerning seismic and geotechnical
issues, although they are object to debate about durability of fluid dynamic or shape memory
alloy dissipators.

Probably it would also be interesting, in terms of procedure, an comparative activity of
different methods on specific study cases, not only in order to carry out a mutual validation,
especially in terms of ability to capture different aspects of complex issues, but also with aim
of being able to deduce applicative procedures or protocols, useful to define a range of data
and solutions in a more holistic as possible kind.

Under this point of view to define the integrated implementation of protocols using different
methods, as already happens routinely in diagnostics for reinforced concrete structures [19]
and same times for wooden ones [20], represents an interesting and strategic research
perspective.

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