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A feasibility analysis on the application of eddy current testing to the detection of the most detrimental defects in historical metallic tie-rods☆

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ABSTRACT

Historical metallic tie-rods have a very important structural role in buildings characterized by arches and vaults because they balance the horizontal thrusts, avoiding the overturning of vertical supports. Nowadays, no information can be found in the literature about the non-destructive detection of possible defects in historical tie-rods and their effects on the in-service structural integrity. On the other hand, many Non-Destructive Techniques are commonly used to inspect modern metallic components and structures, but their viability for cultural heritage is still to be assessed.

In this paper, the application of eddy current testing to the historical metallic tie-rods of the Milan cathedral (Italy) is evaluated, discussed and adapted. The considered historical structures are characterized by a very heterogeneous material, irregular surface geometry and high inherent defectiveness. Recently, in-service failures showed the most detrimental flaws in tie-rods consist of handmade straight scarf forged welds. A first experimental eddy current testing approach, based on off-the-shelf high and low frequency probes, was performed. Results were partially unsatisfactory and showed the challenge is not the maximization of sensitivity and spatial resolution, as in typical modern applications, but their suitable minimization. Consequently, a customized eddy current testing technique, based on a novel low frequency probe, was designed and optimized. Its performance was evaluated by numerical simulations as well as by experimental testing. Based on the satisfactory achievements, the customized eddy current testing technique was applied on site on seven tie-rods. The most significant discontinuities could be effectively detected.

1. Introduction

Historical metallic tie-rods have a very important structural role in buildings characterized by arches and vaults because they balance the horizontal thrusts, avoiding the overturning of vertical supports [1]. Therefore, the analysis of their state of conservation is a decisive step for the assessment of the structural integrity of the whole construction. Nowadays, measurements carried out on tie-rods are mainly aimed at estimating the actual applied forces by performing dynamic modal analyses at different levels of accuracy. A typical procedure is described in Ref. [2]. These commonly applied methods do not account for the detection of possible defects and their effects on the in-service structural integrity. Nevertheless, this issue is crucial in the performance assessment of historical metallic components due to the typical flaws associated to traditional metalworking processes. With regard to tie-rods, in addition to the inherent metallurgical defectiveness related to the low reducing temperature of the ancient furnaces (i.e. heterogeneous matrix, non-metallic slag inclusions, local porosities, and larger voids) [3], macroscopic flaws can be expected due to handmade forging, as well. The typical ones are forged welds, an ancient solid state joining technique used to build up long work-pieces from several short wrought iron bars [4].

Since forged welds are relevant discontinuities pertaining to the whole cross-section, they can reasonably be assumed as the "weakest link", in terms of modern structural reliability, of the "tie-rod structural system". Therefore, their localization, characterization and periodical inspection should not be overlooked, even if, nowadays, no specifically designed methods are reported in the literature on purpose. On the other hand, many established Non-Destructive Testing techniques (NDTs) are today commonly used for detecting flaws in metallic

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materials and alloys, especially in the mechanical and aerospace engineering fields, but the inherent heterogeneity, roughness and defectiveness of historical metallic tie-rods might compromise their effectiveness. In the last years, the authors have studied several NDTs [5] in order to figure out if and how their application could be extended to the cultural heritage field. Among them, at the intermediate scale, Eddy Current Testing (ET) method [6] was investigated by both numerical and experimental approaches. The application of a customized ET probe provided very compelling outcomes, which will be discussed in details in this paper. As well known in the literature [7], ET is an electromagnetic method based on the interaction between an alternating magnetic field and an electrically conductive material inducing surface and sub-surface eddy currents in the sample; defects are detected by monitoring the perturbations of the eddy current flow, in terms of impedance at the sensing coil. Actually, any geometrical (roughness, shape, dimensions) and metallurgical (density, non-metallic inclusions, voids, microstructure, etc.) discontinuities may alter the measured electrical impedance, producing specific and characteristic traces in the acquired polar impedance plane.

The present paper focuses on the case study of ET applied to the historical metallic tie-rods of the Milan cathedral (Italy). Nevertheless, the described methodology can be easily generalized and adapted to other similar cases. In the first part of the manuscript, the case study and its background, including the use of ET procedures based on off-the-shelf probes, are briefly discussed. Preliminary results achieved by ET application, even if rich of suggestions and clues, were just partially satisfactory and hence the next step consisted in the design and optimization of a customized ET inspection technique, based on a tailor-made probe validated by both numerical and experimental results. This approach allowed the successful detection the most detrimental defects in tie-rods both in the lab and on site.

2. A case study: the tie-rods of the Milan cathedral (Italy)

The case study considers the tie-rods of the Milan cathedral (Italy), whose construction started in 1386 (Fig. 1a). Compared to the tie-rods working in other historical buildings, the investigated structural elements have remarkably larger cross-sections: the average dimensions are about 83 × 55mm^2. Their length varies from 5.10 m to 16.4 m, depending on the nave. Moreover, the tie-rods of the Milan cathedral have an even more important structural role, compared to other coeval churches, due to its unusual structural scheme [8].

After the recording of anomalous displacements by the monitoring system active inside the cathedral [19] and the detection of severe damage, two tie-rods were substituted with modern steel bars in 2011 and 2013. They are indicated as T01 and T02 in Fig. 1a and their failures are shown in Fig. 1b and 1c respectively.

The specific causes of the above-described failures were unknown and led to a first multidisciplinary study on tie-rods aimed at achieving more information about the mechanical properties of their material and understanding their state of conservation. In particular, a dynamic modal analysis based on the procedure described in Ref. [9] allowed the estimation of the actual in-service stress of almost all the tie-rods in the cathedral [10]. A non-uniform scenario was discovered: the measured stresses vary from 0 to 150 MPa and several tie-rods showed dynamic anomalies. Furthermore, metallurgical and preliminary NDT investigations revealed a material significantly different with respect to a modern steel or iron: the microstructure is very heterogeneous and a high inherent defectiveness is exhibited at different observation scales [11].

In accordance with the metallurgical features, Vickers hardness varies remarkably: the mean value of the 40 investigated points over a cross section close to the fracture surface of T01 is 132HV10, with a standard deviation of 55HV10. Tensile tests were also carried out according to EN ISO 6892–1 [12] on eight samples machined from T01 [10]. The results showed a very high standard deviation. Particularly, yield stress, tensile strength and elastic modulus were found to be equal to 142 ± 60 MPa, 199 ± 111 MPa and 206 ± 45 GPa, respectively. The density was measured using the hydrostatic weighing method and resulted to be equal to 7792 kg/m^3.

The analysis of the cracks causing the recent tie-rods replacement highlighted that both of them failed at straight scarf forged welds [13]. As demonstrated by proper mechanical characterization testing [14], the fracture toughness at the locations of such welds resulted to be one order of magnitude lower than the one of the base material. For these reasons, forged welds confirm their structural criticality and may be considered the most detrimental defects to be detected and periodically monitored by ET.

Finally, since the electromagnetic properties of the inspected material strongly influence the generation of eddy currents, they were experimentally evaluated, as well, on a chunk of T01 tie-rod. The Rowland ring test and the four points method were used to measure the magnetic permeability (μ) and the electrical conductivity (ρ), respectively. In particular, the latter is equal to (9.1 ± 0.9) x 10^6 S/m, while the achieved magnetic hysteresis cycle (induction and coercive force are about 0.859 T and 889.5 A/m, respectively) highlights a clear ferromagnetic behavior of the considered historical material. It is noteworthy that the obtained experimental values are related to just one tie-rod: they could be either slightly or significantly different for other ones, due to the already described high-scattered metallurgical characteristics of manually forged tie-rods.

Considering the dimensions of the elements and the heterogeneity

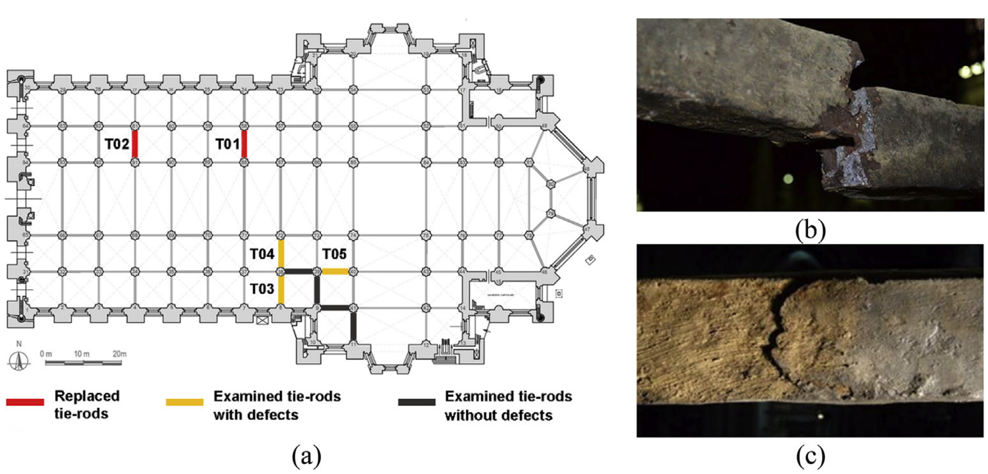


Fig. 1. Milan cathedral: a) scheme of the location of tie-rods discussed in this paper; Failed tie-rods: b) broken in two parts, T01; c) with a visible crack, T02.

of their material, the main requirements for an effective application of ET to historical metallic tie-rods consist in suitable spatial resolution and sensitivity, limited to the detection of dominant defects (i.e. mainly forged welds), and a low time-consuming testing. Accordingly, the first evaluations on the viability of ET to historical metallic tie-rods were performed by using off-the-shelf probes on the two substituted tie-rods in order to understand the main limits of application and how they could be overcome. Summarizing the results, three different ET probes were considered: an absolute high frequency probe, a differential high frequency probe and an absolute low frequency probe (spot probe). These devices provided interesting signals at four specific sections of T02, which resulted to be generated by forged welds after confirmation by a fluorescent Magnetic Particles Testing (MT) inspection, carried out according to ISO 9934–1 [15]. On the other hand, many other secondary, less detrimental, discontinuities were identified as well and, hence, the application of MT became mandatory to classify indications. Moreover, the procedure was very time consuming for on-site application: the examination of the whole tie-rod required four full days [16].

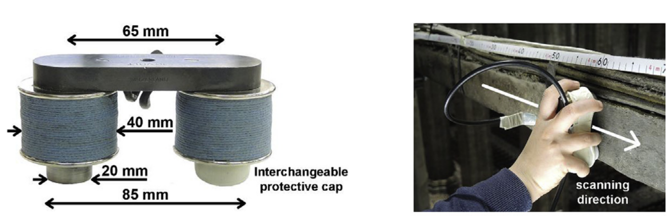
Based on the described background, the research focused on the design and optimization of a prototype purposely built for the discussed application. The compelling results of its on-site application showed the great potentialities of the application of this technique to detect dominant defect in ancient tie-rods.

3. Design and optimization of a customized eddy current probe for historical metallic tie-rods

A dedicated ET technique was, then, developed by designing and optimizing a customized absolute probe and the way to apply it effectively to tie-rods. The target requirements defined for the probe were:

1. a properly wide field of action in order to reduce inspection time;
2. a suitably low magnetic induction in the material in order to lower sensitivity;
3. a properly low operational frequency in order to limit the “skin effect";
4. a suitable dimension of the active tips of the probe in order to lower spatial resolution.

For the sake of brevity, the final configuration of the probe prototype, whose rationale is described and discussed in the remaining part of this Section, is first anticipated. Particularly, all the mentioned requirements were fulfilled by adopting a horseshoe scheme consisting of two copper coils wound on a ferromagnetic and electrically conductive U-shaped metallic core. The most effective number of coils turns was found to be equal to 2000 (1000 for each pole of the probe). The ferromagnetic and electrically conductive metal of the U-shaped core is characterized by a relative magnetic permeability and an electrical conductivity equal to 1000 and $1.45{\cdot}10^6$ S/m, respectively. The optimized operational frequency was determined numerically and resulted to be equal to 500 Hz. Fig. 2a shows the final version of the prototype. The poles are provided with screwed interchangeable polyethylene caps as a protection against wear.



(a) (b)

Fig. 2. The horseshoe eddy current probe (a) prototype; (b) on site application.

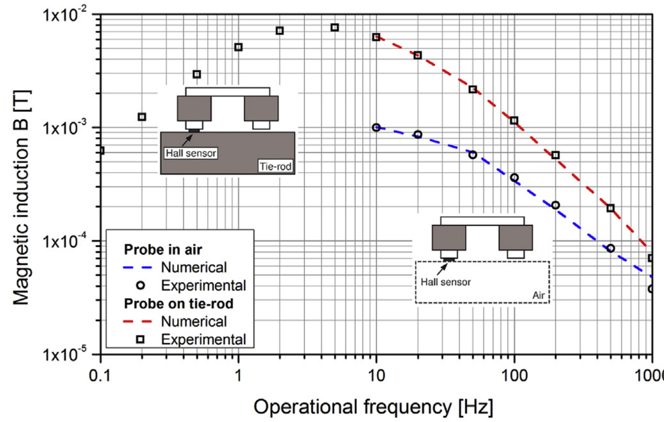


Fig. 3. Validation of the numerical model by experimental acquisitions of magnetic induction on T01 tie-rod.

The described prototype of the probe and its application to heterogeneous ferromagnetic tie-rods define a complex electro-magnetic system that has no simple analytical solutions, at least to the authors' knowledge. For this reason, the design study was carried out by means of 3D ET numerical models implemented in the CIVA^{nde} dedicated software package v. 2017 [17]. In particular, the final prototype of the probe was modelled implementing its geometry and operational parameters, while the tie-rod was modelled as a smooth prism (without defects) characterized by the electromagnetic properties derived experimentally (see Section 2). The experimental validation of the numerical model was carried out by acquiring the trend of magnetic induction as a function of the operational frequency. To this aim, a Hall sensor (Honeywell SS94A1F), having a sensitivity equal to 25 mV/Gauss, was positioned in the center of one pole. The probe was kept either in air (frequency range 10–1000 Hz) or coupled to a chunk of T01 tie-rod (frequency range 0.1–1000 Hz). The same two configurations were then simulated by the numerical model (frequency range between 10 Hz and 1000 Hz) and the results compared to the experimental evidences. In Fig. 3, the obtained experimental results are compared with the numerical ones showing the good fit of the model.

The validated numerical model was first used to design the general dimensions the probe must have in order to provide a wide field of action and, consequently, to allow a reasonable inspection time (requirement #1 above). A horseshoe morphology was adopted because it can be able to inspect a whole side of a tie-rod without requiring multiple passes as for the considered off-the-shelf ones. The geometrical dimensions of the probe were then defined (Fig. 2a) considering the maximum (71 mm wide and 100 mm deep) and the minimum (40 mm wide and 60 mm deep) dimensions of the sections of the tie-rods located in the Milan cathedral. Moreover, it was also kept into account that the larger side of tie-rods, i.e. their depth, is usually the most accessible one for on-site inspections. No defects were introduced in the model during these analyses dealing with the field of action. Fig. 4 shows the simulated magnetic field inducted in the maximum and the minimum considered sizes.

As can be seen, the chosen morphology and dimensions of the probe actually allow inspecting the whole side (depth) of both tie-rods in just one take, suggesting the likely applicability to all the tie-rods located in Milan cathedral (Fig. 2b). On the other hand, the magnetic induction generated along the line connecting the poles of the probe is not uniform and, consequently, the sensitivity is expected to be non-uniform, as well. However, this is not a critical point for the discussed application because the defects of interest (straight scarf welds) affect the whole section of tie-rods.

Switching to the electro-magnetic performance of the probe, it is first worth noticing that magnetic induction (requirements #2 above) and operational frequency (requirements #3 above) are strictly related

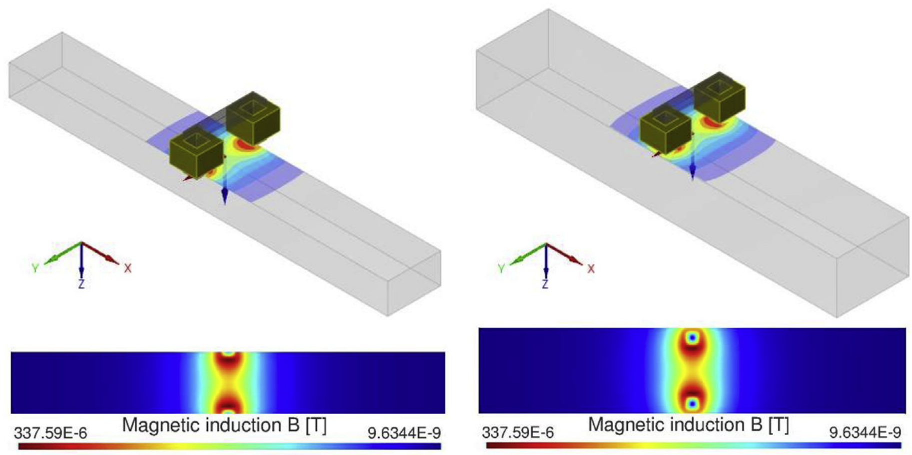


Fig. 4. Field of action of the customized probe in terms of magnetic induction: a) case of the smallest tie-rod in the Milan cathedral; b) case of the largest tie-rod in the Milan cathedral.

to each other and, consequently, cannot be studied independently. Nevertheless, the number of parameters involved in the definition of the magnetizing performance of an ET probe is rather high (number of coil windings, material and diameter of the coil wire, material and shape of the core, etc.). Moreover, it is also known [6] that, given the component/material to be inspected, the number of combinations, able to provide the same physically meaningful magnetic induction, of such parameters can be countless. In order to ease the study, the here adopted strategy was then to keep the hardware parameters fixed, while the operative ones (i.e. the operational frequency and the nature of the inspected flaws) were varied among the analyses. The material set for the electrically conductive and ferromagnetic U-shaped metallic core is a ferritic stainless steel characterized by a relative magnetic permeability and an electrical conductivity equal to 1000 and $1.45{\cdot}10^6$ S/m, respectively. This material was chosen because it is effective against environmental corrosion (providing a prospective long durability of the probe during time) and relatively cheap with respect to other stainless steel grades. The rationale on choosing an electrically-conductive core is based on the hypothesis it can decrease the primary magnetic field by generating eddy currents within itself, so helping to keep low the magnetic induction in the examined component, as required by the present application. This hypothesis was verified and confirmed by the experimental evidences shown in Fig. 3. As can be seen, magnetic induction in the T01 tie-rod initially increases with the operational frequency (until a value equal to about 5 Hz) and then rapidly decreases to very low values, so lowering sensitivity. Considering the coil windings, a standard copper wire having a diameter equal to 0.2 mm was adopted. The number of turns of the windings was fixed to 1000 for each of the two coils. The exciting current of the two coils was fixed to 5 mA.

The numerical sensitivity analysis of the influence of the operational frequency was carried out based on the simulation of the inspection of a number of flaws of different nature, shape and dimensions. In particular, three frequency values (200 Hz, 500 Hz and 1000 Hz) and the following flaws were considered (Fig. 5).

1. Cracks: through-thickness crack-like slits having a depth varying between 0.1 mm and 3 mm. Contrarily to real forged welds, the simulated cracks were perpendicular to the inspection plane because the adopted software does not allow modelling inclined cracks.
2. Inclusions: regions of the simulated tie-rod characterized by different electro-magnetic properties, in particular those of silica inclusions observed in tie-rods [11]. The considered dimensions varied in terms of depth, width and length in the range of 0.1–3 mm, 0.1–3 mm and 0.1–10 mm, respectively.
3. Surface irregularities: surface regions characterized by an irregular profile. The considered dimensions varied in terms of depth and width in the range of 0.1–3 mm and 0.1–20 mm, respectively.

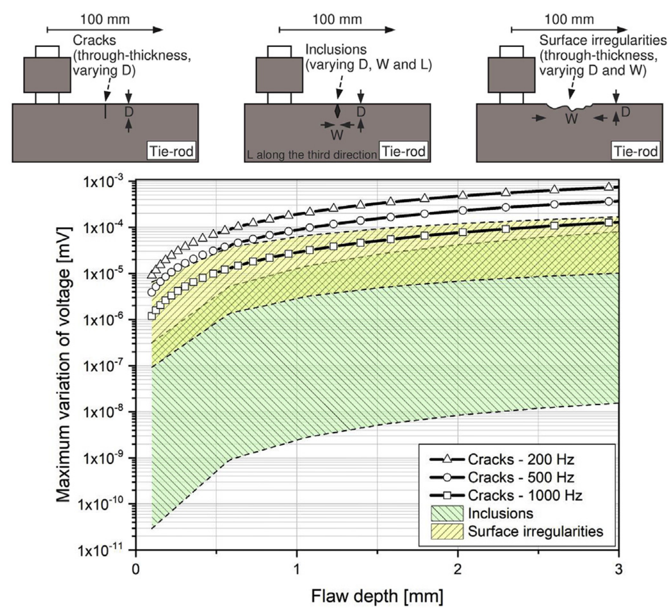


Fig. 5. Numerical sensitivity analysis, about the operative frequency, based on flaws of different nature, shape and dimensions.

The sliding movement of the probe on the examined surface was simulated, as well. The analyses were carried out following a full factorial plan in order to check all the possible combinations of the parameters.

Fig. 5 shows the results of the full factorial plan in terms of the maximum variation of voltage, through the two coils, versus the depth of the considered flaws. As expected, increasing the depth of the flaws, the signal responses tend to saturation, likely due to the limits of penetration of eddy currents. On the other hand, a comparative discussion on sensitivity is more interesting. The reported shaded areas represent the regions of the plane covered by all the ET responses of inclusions and surface irregularities: such areas partially overlap, but a tendency to a higher detectability (i.e. higher values of the variation of voltage) is observed for the case of surface irregularities. Nevertheless, inclusions

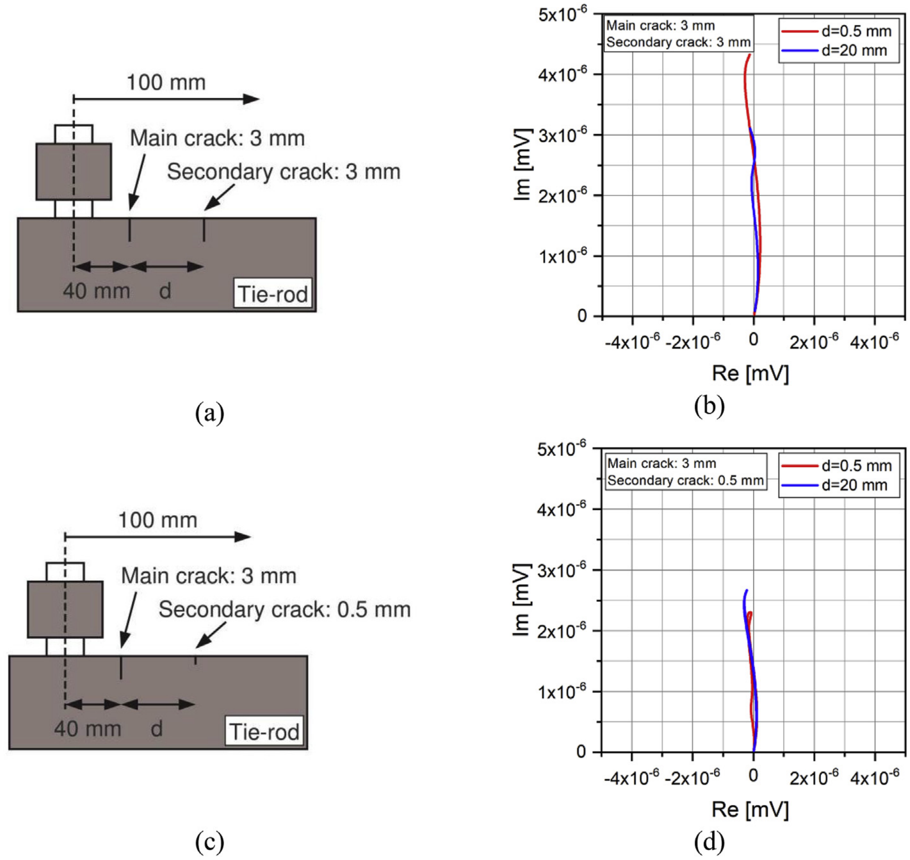


Fig. 6. Results of spatial resolution for two exemplificative cases: a) a main 3 mm deep crack versus a secondary 3 mm deep crack; b) polar plot of case (a); c) a main 3 mm deep crack versus a secondary 0.5 mm deep crack; d) polar plot of case (c).

and surface irregularities are disturbing elements for the present application, where the most detrimental flaws, i.e. crack-like straight scarf forged welds, are the main inspection target. Superposing the responses due to cracks to the shaded areas, it is possible to highlight an operational frequency equal to 1000 Hz falls inside the region of surface irregularities, so setting some uncertainty on a clear detectability of the cracks themselves. On the contrary, an operational frequency equal to 200 Hz seems to outdo the job. An optimized value of the operational frequency is, then, equal to 500 Hz, whose trend is located just above the upper bound of the shaded areas. This frequency value was finally chosen to operate the probe prototype.

The last requirement, about spatial resolution (#4 above), was studied by a numerical full factorial plan based on simulated inspections of two crack-like flaws having a depth varying from 0.5 mm to 3 mm and a relative distance varying from 0.5 mm to 20 mm. The diameter of the poles of the probe was fixed to ∅20 mm, i.e. larger than the largest commercial probe available on the market, and the sliding movement of the probe on the examined surface was simulated, as well.

Fig. 6 summarizes the results, for two exemplificative cases, in terms of polar plots of the maximum variation of voltage through the coils: a main 3 mm deep crack versus a secondary 3 mm deep crack (Fig. 6a) and a main 3 mm deep crack versus a secondary 0.5 mm deep crack (Fig. 6c). Unfortunately, it was quite difficult to get significant information on spatial resolution from these polar plots because both the phases and the magnitudes are very similar for all cases. More insight, instead, could be achieved analyzing separately the real and imaginary parts of the polar plots in terms of the instantaneous position of the probe during the simulated inspection (Fig. 7).

First, even if the imaginary parts of voltage are one order of magnitude higher than the real ones, they still do not provide a clear and definite information on spatial resolution (Fig. 7b and Fig. 7d). Nevertheless, real parts (Fig. 7a and c) show significant variations, suggesting their possible effective use for the definition of spatial resolution. In particular, Fig. 7a shows that, when the two 3 mm deep cracks are very close (0.5 mm from each other), just one local voltage maximum is observed at their location (40 mm), so that spatial resolution is not sufficient to recognize them separately. On the other hand, when the two cracks are far (20 mm), two local voltage maxima are observed at their locations (40 mm and 60 mm) and spatial resolution is fully achieved. The same conclusion can be drawn for the case of the main 3 mm deep crack versus the secondary 0.5 mm deep crack (Fig. 7c), even if it is worth noticing that the curves are no more symmetrical due to the different depths of the considered cracks. The value of the spatial resolution of the prototype probe is, then, included in the range between 0.5 mm and 20 mm. To determine a more exact value, Fig. 8 shows an enlargement of the region of the local maximum at 40 mm and the curves for three different distances between the 3 mm deep cracks: 6 mm, 7 mm and 8 mm.

The distance equal to 8 mm is the smallest one at which a significant separation of two local maxima, and the disappearance of the single one, begins to be appreciated. The same value could be determined by analyzing all the other configurations of the full factorial plan, so it represents the spatial resolution of the prototype, which is considered low enough for the present application.

The designed ET probe was finally verified experimentally by inspecting the two opposite larger sides (depth) of T02 tie-rod by the probe prototype. The resulting pattern survey is shown in Fig. 9: as can be seen, all indications corresponding to forged welds, and highlighted by MT, were detected, while almost all the other ones, clearly detected by off-the-shelf probes, were neglected and not recognized. Moreover, the total inspection time lasted just one hour. It can be concluded that the developed ET inspection technique is actually effective in detecting

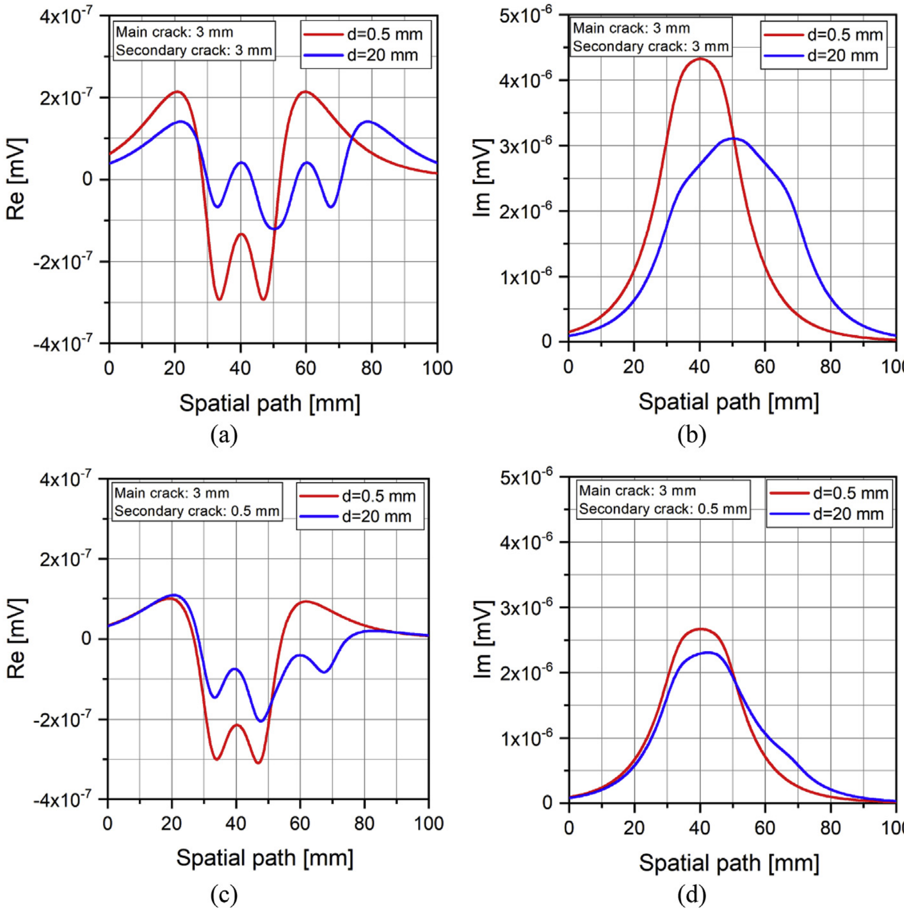


Fig. 7. Analysis of the real and imaginary parts of the maximum variation of voltage through the coils in terms of the instantaneous position of the probe during the simulated inspection.

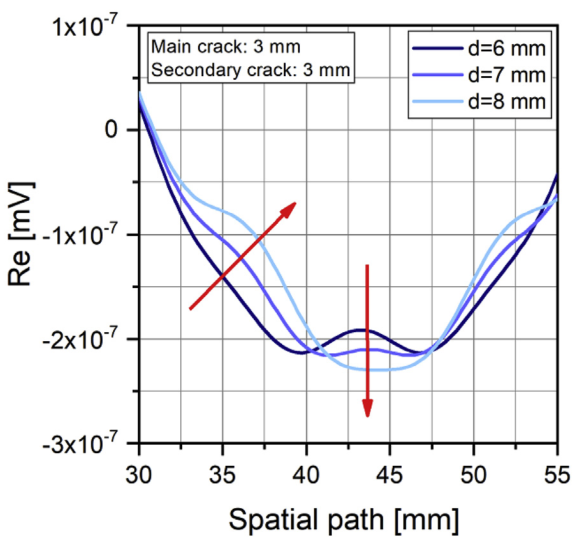


Fig. 8. Quantification of the spatial resolution of the prototype.

just the most detrimental defects in historical metallic tie-rods. Furthermore, the customized method is not time consuming and, hence, it can be reasonably used for a more extensive on-site campaign.

4. On site application of the developed ET inspection probe

The customized ET technique was applied on site on seven tie-rods placed close to the tiburio of the Milan cathedral (Fig. 1a), which was one of the most suffering areas of the cathedral [8] and still today shows a quite interesting crack pattern of the masonry vaults [18].

As previously anticipated, ET was performed along the depth of the cross-sections. The position of indications along tie-rods was taken into account as well as their amplitude. The highest emphasis was given to local peaks located on opposite sides and shifted by 100–200 mm, because these occurrences are most likely due to the presence of dominant defects at forged welds. In order to provide additional insight, 20 Mpixel resolution pictures of the areas corresponding to ET indications were taken by a Canon EOS 600 D high performance camera with EF50mm f/2.5 compact macro lens, so allowing close-up shooting up to 60 pixel/mm.

The inspection of each element lasted about 2 hours, including the photographic survey. Many indications (i.e. 72) were detected on the investigated tie-rods. The indication characterized by the highest detected amplitude (i.e. 13.6 Ω) was recorded on T03. The corresponding impedance plane is shown in Fig. 10a. At this location, a relevant local defect was found on the lower edge of the tie-rod along a trace recalling the typical welding line shape (Fig. 10b): its maximum opening is about 3 mm. On other two tie-rods defects were recognized, namely on T04 and T05. On the first element, an open crack, involving three sides of the tie-rod, can be observed. Such a crack, on one of the vertical sides, affects about the 50% of the cross-section depth and a maximum opening of about 0.3 mm could be measured (Fig. 10c). As regard T05, a partially open crack could be detected, through visual inspection, on the lower side of the tie-rod (Fig. 10d). Considering the other indications, most of them corresponds to evidences suggesting the presence of a forged weld that cannot be easily observed due to the operative conditions, such as a variation of the cross-section geometry or a trace

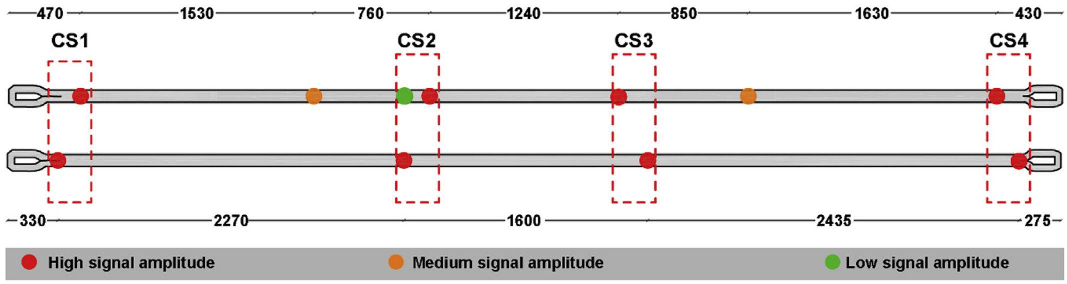


Fig. 9. Pattern survey of the indications achieved by the horseshoe probe prototype.

having the typical welding line shape. Differently to the previously discussed cases, the signal at these locations varies gradually and hence it is reasonable to assume the presence of a not damaged forged weld. The different impedance values of balanced bridge before and after forged welds may reveal the variation of the material properties due to the heat treatment.

5. Concluding remarks

In this paper, the use of eddy current testing applied to the field of cultural heritage is discussed, with particular attention to the wrought iron tie-rods of the Milan cathedral case study. Conclusions can be summarized as follows:

1. The eddy current non destructive method was studied to understand how it can be adapted and improved to allow detecting the most detrimental flaws in historical metallic tie-rods, with special attention to the case study at issue;
2. Compared to modern steels and irons, the considered historical tie-rods are characterized by a very heterogeneous metallurgical structure, irregular surface geometry and high inherent defectiveness;
3. Recent in-service failures showed the most detrimental flaws in tie-rods are the handmade straight scarf forged welds, which, consequently, represent the main defects to be detected and periodically monitored by eddy current testing;
4. A preliminary experimental eddy current testing approach, based on off-the-shelf high and low frequency probes, showed the main challenging aspect is not the maximization of sensitivity and spatial resolution (as in typical modern applications), but their suitable minimization;
5. A customized eddy current testing technique was developed, based on a novel low frequency probe which was purposely designed and manufactured for the discussed application. The features of the probe were optimized by numerical analyses validated on experimental results;
6. The developed eddy current technique was successfully validated in the lab on the original failed tie-rod replaced from service, allowing the detection of just the most detrimental forged welds;
7. The developed eddy current technique was, then, applied on site to seven tie-rods of the Milan cathedral. Inspections allowed a clear and quick detection of several indications on each tie-rod, most of which are probably forged welds. Among them, three critical regions were recognized characterized by the presence of visible relevant discontinuities.

The eddy current technique demonstrated its effectiveness in detecting the most detrimental cracks in historical metallic tie-rods. In order to perform a reliable assessment of the global safety of the element, the next step should be the precise measuring of crack dimensions. Multi-frequency ET may provide some first indications, due to the varying sensitivity to the depth of shallow cracks. Ultrasonic phased array is an effective method on purpose. However, since it is a punctual technique, it cannot be employed on the whole tie-rod volume and, hence, it is well complemented by a preliminary screening of most critical sections by eddy current inspection.

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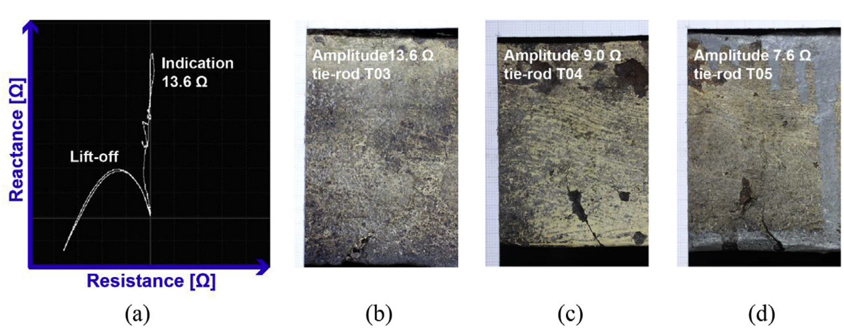

Fig. 10. a) Impedance plane at defect on T03; defect on b) T03, c) T04 and d) T05.

References

[1] Mastrodicasa S. Static failures in building structures (Dissesti statici delle strutture edilizie). Milano: Hoepli; 1974. (in Italian).

[2] Lagomarsino S, Calderini C. The dynamical identification of the tensile force in ancient tie-rods. Eng Struct 2005;27(6):846–56.

[3] Nicodemi W. The civilisation of iron: from prehistory to the third millennium. Milano: Riva Group; 2004.

[4] e Copperi Musso. Details of wall constructions and building finish: part 1.: masonry works (Particolari di costruzioni murali e finimenti di fabbricati: parte 1.: opere muratorie). Turin: Paravia; 1877. (in Italian).

[5] Bellanova M. A multidisciplinary and multiscale strategy for the assessment of the structural safety of historical metallic tie-rods PhD diss. Milano: Politecnico di Milano; 2017.

[6] The American Society For Nondestructive Testing. Nondestructive testing handbook. third ed. ASNT; 2004.

[7] García-Martín J, Vázquez-Sánchez J Gómez-Gil e E. Non-destructive techniques based on eddy current testing. Sensors 2011;11(3):2525–65.

[8] Ferrari da Passano C. Il Duomo rinato [Milan cathedral reborn]. Vigevano: Diakronia; 1988.

[9] Tullini e N, Laudiero F. Dynamic identification of beam axial loads using one flexural mode shape. J Sound Vib 2008;318(1):131–47.

[10] Vasic M. A multidisciplinary approach for the structural assessment of historical constructions with tie-rods PhD thesis Milan: Politecnico di Milano; 2015 P. thesis.

[11] Bellanova M, Baggioli A, Rivolta B, Felicetti e R, Cornaggia A. Metallurgical and mechanical characterization of the historical tie-rod of Duomo di Milano. XXXI° international conference of cultural heritage, Brixen. 2015.

[12] ISO 6892-1. Metallic materials. -Tensile testing - Part 1: method of test at room temperature. 2016.

[13] Bellanova M, Felicetti R. A multidisciplinary strategy for the inspection of historical metallic tie-rods: the Milan cathedral case study. Int. J. Archit. Herit. 2019. https://doi.org/10.1080/15583058.2018.1563228. 19p.

[14] Gianneo A, Bellanova M, Carboni M, Felicetti R. Study on the influence of defects on the strenght of metallic historical tie-rods. 12th International Conference on non-destructive investigations and microanalysis for the diagnostics and conservation of cultural and environmental heritage (Art.17), Turin, November 22nd/24th. 2017. 2017.

[15] ISO 9934-1. Non-destructive testing - magnetic particle testing - Part 1: general principles. 2015.

[16] Bellanova M, Carboni M, Felicetti R, Gianneo A. Flaws detection on historicial metallic tie-rods. National conference on non-destructive testing, monitoring and diagnostics (AIPnD), Milan, October 21-23. 2015.

[17] CIVAnde. User's manual. 2017.

[18] Cardani G, Coronelli D, Angjeliu G. Damage observation and settlement mechanisms in the naves of the Cathedral of Milan. Structural analysis of historical constructions: anamnesis, diagnosis, therapy, controls: proceedings of the 10th international conference on structural analysis of historical constructions, Leuven, Belgium. 2016.

[19] Giussani A. Relazione sulle misure eseguite per il controllo delle deformazioni del Duomo di Milano nei giorni 21, 23 e 28 Novembre 2011 e 3 Dicembre 2014 [Report on deformation monitoring in the Cathedral of Milan on dates 21, 23 and 28 November 2011 and 3 December 2014]. Lecco: Politecnico di Milano; 2015.