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Using commercial UHF-RFID wireless tags to detect structural damage

Amedeo Gregori[a], Chiara Castoro[a]*, Antonio Di Natale[b], Micaela Mercuri[a], Emidio Di Giampaolo[b]

[a] *Department of Civil, Construction-Architectural and Environmental Engineering, University of L'Aquila, Italy;*
[b] *Department of Industrial and Information Engineering and Economics, University of L'Aquila, Italy.*

Abstract

The use of commercial UHF-RFID tags for civil engineering purposes has been investigated, specifically for the monitoring of out-of-plane displacements of brick walls, representing an application novelty since commercial tags are usually used in logistics and other purposes. The feasibility of the application of this technique was assessed by laboratory and in situ experimental campaign. The response of the Tags in laboratory environment demonstrated to be satisfactory, proving that the application of these wireless RFID tags is feasible, potentially very reliable. In situ experiment showed a weaker response of the Tags due to environmental interference caused by the high presence of metal which negatively affected the transmission of the electromagnetic signal, and consequently the indirect measurements of displacements. Despite some limits, the application is promising and opens new scenarios for the design of new wireless tags suitable to meet the required needs.

Keywords: UHF-RFID tags; wireless sensors; damage detection; structural monitoring;

1. Introduction

Nowadays Structural Health Monitoring (SHM) is going on resorting to intelligent monitoring systems to study the characteristics and the evolution of damaged infrastructures or the behaviour of the structures for loading and fatigue

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* Corresponding author.
E-mail address: chiara.castoro@graduate.univaq.it

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effects as well as material aging (Li et al. 2016, Seo et al. 2016, Kulkarni et al. 2008, Dissanayake and Karunananda 2008). In particular, new wireless methodologies are increasingly used and developed, since the use of wireless sensor networks (WSNs) permit a fast and easy installation even in measurement points difficult to access and allow to spread over the structure a large number of sensors, to obtain a distributed assessment of the structural condition, with low costs of the devices and low maintenance costs. In particular, this new technique shows to be effective for the monitoring of the historical structures belonging to the architectural heritage, that manifested extensive damage phenomenon and collapse during the last earthquakes (Ramos et al. 2013, Pallarés et al. 2021, Barsocchi et al. 2021, Mercuri et al. 2021b). The research recently investigated the use of antennas operating at microwave frequency as wireless sensing units (Roy et al. 2010; Caizzone et al. 2014; Caizzone & Di Giampaolo 2015; Caizzone et al. 2015; Poggi et al. 2013). These devices have a long lifetime without or negligible maintenance and can be widely distributed or embedded everywhere. The main novelty in these devices is the lack of a specific sensing unit, in fact the antenna is itself the sensor. Some include a Radio Frequency Identification (RFID) microchip to perform the modulation of the backscattered signal. The small change of the shape of the antenna, in consequence of the forces applied to the structure where the antenna is stuck on, shifts the resonance frequency of the antenna that is remotely detected by means of a power measurement or, equivalently, a measurement of the change of the radar cross section of the antenna (Gregori et al. 2019). In this study, the use of pure commercial RFID tags (not being embedded in antennas) has been investigated to be employed for civil engineering purposes, specifically for the monitoring of out-of-plane displacements of a brick wall. Under the excitation of the seismic action, masonry walls are contemporaneously subjected to both in-plane and out-of-plane actions (Mercuri et al. 2020). As a matter of fact, the out-of-plane collapse of peripheral walls is the most recurrent damage observed in post-earthquake surveys and it occurs at lower seismic intensities than the in-plane ones (Mercuri et al. 2021). The RFID technology is used commercially for the identification and/or automatic storage of data relating to objects or animals. It is based on the storage capacity of certain electronic labels, called Tags (or transponders), of information regarding the object to which it is coupled. These tags respond to remote interrogation by devices called readers. Through the use of RFID technology, it is possible to create a system of interconnected objects that allow the collection and processing of data in a single large global network. Specifically, an RFID system consists of four fundamental elements:

1. The Tag, which is a small device consisting of an integrated circuit (IC) with simple control logic functions, with memory, incorporated into a paper or plastic label. Once activated the Tag is able to transmit the information it contains. Such information can be not only read, but also modified through write operations. Generally, the data contained in the tag memory has a unique identification code.

2. The antenna allows to send and receive the data contained within the tag through electromagnetic waves. These waves are collected by the antenna contained in the RFID tag and used to power the microchip which releases information to be returned to the reader.

3. The Reader is the element of the system that has the task of reading and filtering the information on the Tags. The Antenna and readers can be combined in a single device or be two distinct devices.

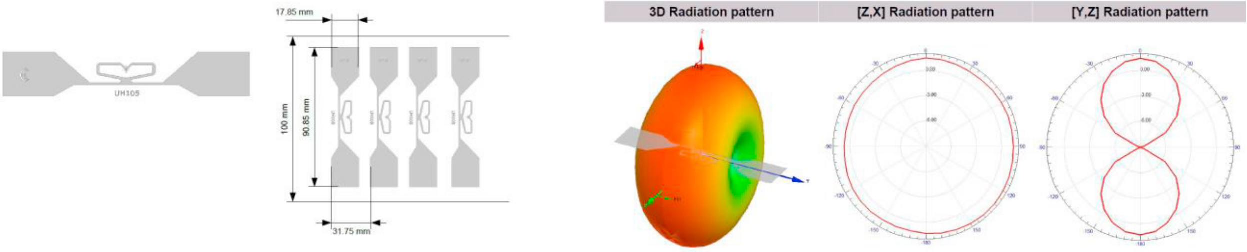
4. The management system (host computer, server) is the information system that is connected to the network and to the reader. This system allows, starting from the identification codes coming from the tags, to obtain all the available information associated with the objects and to manage this information for the purposes of the use case.

Tags can vary in shape, size, material, and operating frequency, but all of these can be grouped into three large families: Active, Passive, and Semi-Passive or Semi-Active. In this study, passive tags have been used. Passive tags do not have their own energy source but receive it from the signal coming from the Antenna. In particular, passive UHF-RFID tags have been used. Tags of this type are part of the UHF class which operates at 867/868 MHz. The distances in which they can operate are of few meters, up to 30 meters.

In this study the commercial UHF-RFID tags (UH105) were used to monitor the displacements of a brick wall 2.70 m high and 1 m wide, subjected to out-of-plane actions induced by a concentrated load along the middle of the wall. The innovation of this research is represented by the novelty of the application of this type of sensors in civil engineering. Since no literature is reported about this type of application of the RFID tags for civil engineering monitoring purposes, an experimental test was first conducted in the laboratory room in a controlled environment to investigate the feasibility of the application, and then performed on site.

2. Application of the UHF-RFID tags for civil engineering purposes: experimental investigation

The commercial UH105 tags have been used (figure 1). UH105 tag is a completely passive transponder made by LAB-ID. Its dimensions are 90.85×17.85 mm^2 and consists of an aluminum dipole antenna (9 mm thick) and a polyester (PET) substrate with a thickness of 38 mm. An EPC Class 1 Gen2 Impinji Monza 5 chip, operating in the 840 MHz – 960 MHz band, is connected to the antenna. This tag has been designed to be used in logistics and in fields where there is a high concentration of tags. This is possible thanks to its good radiative properties, and to its good properties of insensitivity to its orientation in the space in which it is positioned, that allow it to be detected at a great distance.



a) b)

Fig. 1. a) Detail of the commercial UHF-RFID tag: UH105; b) Radiation pattern of the UH105 tag.

The main features of this commercial tag are reported in Table 1 and figure 1 b).

Table 1. Features of the commercial UHF-RFID tag.

Composition	Material	Thickness (μm)
Top	Aluminium	9 ± 5%
Support	Polyester PET	38 ± 5%
Tag	Operating frequency	Operating temperature
	840 - 960 MHz	-40 °C to +85 °C

2.1. Monitoring tags displacements under out-of-plane actions: laboratory experiment

An experimental campaign was carried out in the laboratory to assess the feasibility of using UHF-RFID tags for the monitoring of out-of-plane displacements. The experimental set-up was organised considering the next in-situ distances and spaces, in order to make then a comparison between the results in the same conditions, except for the environment. It is known, in fact, that the RFID tags and the antenna are sensitive to the presence of metal in the environment since they work with electromagnetic waves. Each tag reflects part of the electromagnetic power received, which is detected by the Reader antenna. The phenomenon of reflection of the electromagnetic waves is known as "backscattering" and is similar to that on which the operation of radar systems is based. The presence of metal or other obstacles around the electromagnetic field can alter or shield the signal, modifying the expected results. For this reason, the experiment was carried out first in the laboratory room where the presence of metal was very low, and no environmental obstacle was present. The experimental campaign considered six tags positioned following a 3x2 grid. An ID number identified each tag, so they could be named as follows: Tag 1.4, Tag 2.1, Tag 1.3, Tag 1.1, Tag 1.5, Tag 2.2.

The tags were positioned on a polystyrene panel, which acted like a "transparent" panel to the electromagnetic waves and did not modify the backscattered signal. The tags were positioned as depicted in Figure 2. The Antenna was positioned in front of the panel, at a distance of 60 cm. The projection of the center of the antenna on the panel falls at a distance of 3 cm below the central axis of the tags of the central row (in red in Figure 2). The panel was subjected to out-of-plane displacements, orthogonal to the plane of the panel and the antenna, by the use of a micrometric screw. In particular, the panel was moved towards the antenna at steps of 5 mm, reaching the final distance of 60 mm respect to the starting position. The Antenna worked at 867 MHz and the acquisition system was set with a power of 20 dBm which was sufficient for a correct reading of each tag.

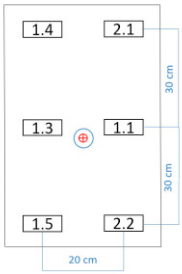


Fig. 2. Laboratory campaign: scheme of the experimental set-up. In red, the projection of the center of the antenna on the polystyrene panel.

2.2. Results of the laboratory experimental campaign

In the experimental campaign the acquisition of the displacement measurement was performed for each step (each 5 mm). In the following figures, the results of the measurements are reported plotting the mobile mean and standard deviations of the phase, referring to each step of measurement. This was done for each tag. Also the RSSI "Received Signal Strength Indicator" is plotted and indicates the good quality of the signal for values around -52 dBm.

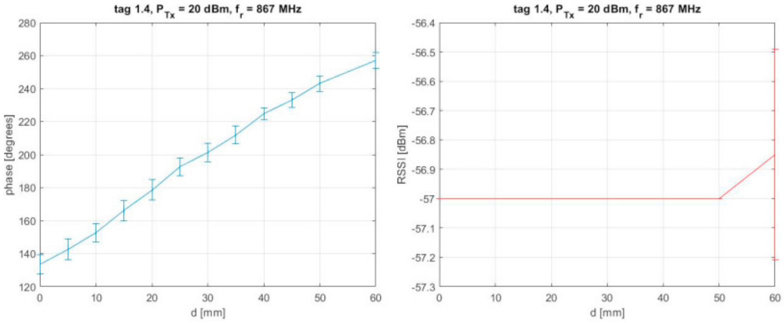


Fig. 3. Laboratory campaign: Tag 1.4. Mean and standard deviation values of the phase and relative RSSI values registered for each step of measurement.

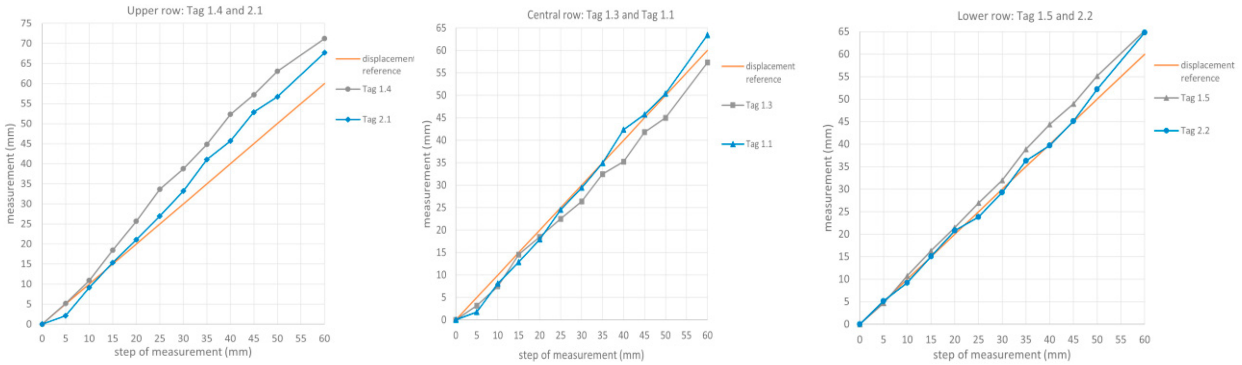
In figure 3 are reported the results of the acquisition system of the Tag 1.4. The mean values and standard deviation values of the phase registered for each step of measurement are reported together with the relative RSSI values.

As can be observed from the graphs of figure 3, a difference in the phase values is detected from the starting point 0 mm to the final point 60 mm, in particular increasing values of the phase are observed for each step of measurement. The same is observed for the other Tags. This means that the Tags are sensitive to the displacements that have been imposed to them in each step of measurement. The RSSI values are quite constant and with very small fluctuations for the other tags, anyway acceptable. To assess the feasibility of this new wireless monitoring application, the phase difference between a certain step of measurement and the previous one has been converted into distance difference by using the following equation:

$$d - d_0 = \frac{(f - f_0) \cdot \lambda}{4 \cdot 180} \tag{1}$$

where $f - f_0$ is the phase difference associated to a certain step of measurement and the previous one, λ represents the wavelength that in this case is equal to 0,346 m. From this formula, it is determined the distance difference $d - d_0$ that occurs along the three-dimensional path of the electromagnetic waves when the Tag moves from a certain position to another. So, it's the spatial difference between the paths linking the center of the antenna and the Tag when it moves.

To determine the distance difference and so the displacement of the tag in one direction (the out-of-plane direction, orthogonal to the polystyrene panel on which the Tags are positioned), that is the direction in which the movement has been imposed, it has been necessary to geometrically calculate it by a 3D modelling of the set-up. The results of displacements detected by the Tags have been plotted in graphs, compared to the actual displacements imposed (plotted as displacement reference) in order to assess the feasibility of the technique. For a faster comprehension, the displacement results have been coupled according to the Tags position in rows (see figure 2), distinguishing in upper row, central row, and lower row Tags. In the graph of figure 4 a) are reported the displacements detected by Tag 1.4 and 2.1 compared to the actual displacements imposed to the panel. Figure 4 b) reports the displacements detected by central row Tags 1.3 and 1.1 and figure 4 c) shows the displacements of the lower row Tags 1.5 and 2.2.



a) b) c)

Fig. 4. Laboratory campaign results: a) Upper row Tag 1.4 and 2.1; b) Central row Tag 1.3 and 1.1; c) Lower row Tag 1.5 and 2.2.

As can be seen from the graphs, the Tags all show quite matching displacements. This is surprising, considering the intrinsic measurement errors of the reader itself and the standard deviations of the mean values calculated for the phase's measurements. More in depth, we can also observe that for the upper row Tags there is the higher error, in particular for Tag 1.4. It can be supposed that this higher error is due to the position of the antenna that is more distant from these Tags, compared to central and lower row Tags (see Figure 2). Since the Tags are positioned on a rigid panel which translates rigidly, the discrepancies in the results could be checked into the environment. Tag 1.4, in fact, is near a plasterboard wall. It can be supposed that the metallic components of the plasterboard wall could have influenced some way the signal, reducing the response of the Tag. Also Tags 1.3 and 1.5 are at the same distance from the plasterboard wall, but their response is better since the antenna is nearer.

2.3. Monitoring tags displacements under out-of-plane actions: IN SITU experiment

The UHF-RFID tags were used to monitor the displacements of a brick walls 2.70 m high and 1 m wide, subjected to out-of-plane actions induced by a concentrated load along the middle of the wall. The brick wall was realized and tested in situ, in a building site. Fixed constraint is placed along the entire base of the wall and hinge constraint is applied at the top of the wall which is anchored to the metal frame. The tags were positioned following the 3x2 grid with the same set up distances of the 1st laboratory campaign, to make a comparison with the same geometric conditions. The antenna was positioned at a height of 1.27 m. The distance between the center of the antenna and the wall was 0.60 m. The wireless acquisition of data was made with a power of 20 dBm. To avoid the possible electromagnetic influence of the components of the wall material on the response of the tags, the tags were placed on small 5 cm thick polystyrene spacers. To validate the measurement a wired displacement transducer was positioned at the half of the wall, in correspondence of the maximum displacement of the wall and in correspondence with the position of the two central row tags. The displacement transducer is positioned about 20 cm from the left-side Tag.

In this case, the wall will not translate rigidly because is constrained and is subjected to deformations. This means that the Tags will not have the same displacements like in the laboratory experiment. The set up for the experimental test is shown in Figure 5 a). The measurement acquisitions were made at each step of measurement (5 mm). Figure 5 b) shows a detail of the wall with deformation and cracks. As the displacement increases, the cracks appear, and the deformation of the wall increases. The final maximum displacement and deformation are shown in Figure 5 c).

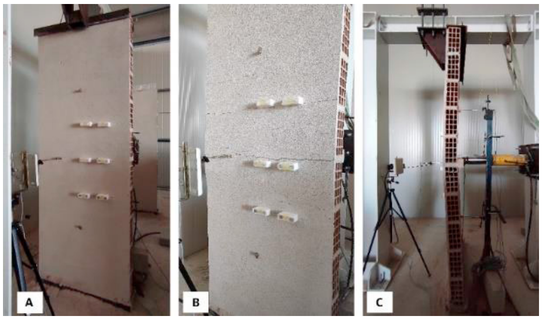


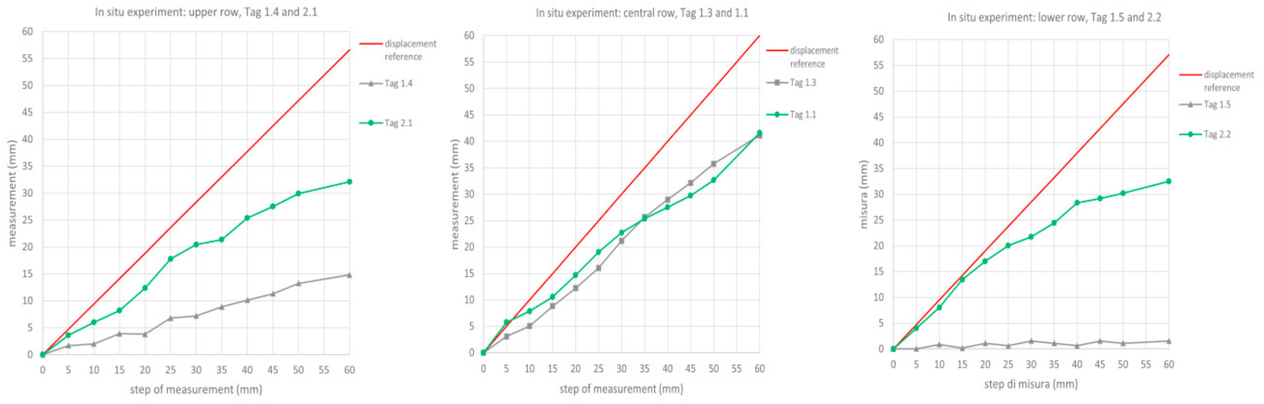
Fig. 5. In situ experiment on the wall: a) Set-up of the experimental test; b) Detail of the Tags. Deformation and cracks appear at increasing the displacement; c) Complete deformation of the wall at the final displacement of 60 mm.

3. Results of the in situ experimental test

3.1. UHF-RFID tags displacements compared to wired transducer displacements.

The mean values and standard deviation values of the phase registered for each step of measurement are reported for each Tag together with the relative RSSI values. Increasing values of the phase are observed for each step of measurement from the starting point 0 mm to the final point 60 mm. This means that the Tags are sensitive to the displacements obtained at each step of measurement. The results of displacements detected by the tags have been plotted in the following graphs, compared to the displacements detected by the wired transducer. It is important to point out that the wall is subjected to deformations as the load cell imposes forces in the out-of-plane direction. For this reason, for the Tags positioned in the upper and lower rows it is not possible to consider as reference the measurements detected by the wired transducer that is positioned in correspondence of the central row Tags, i.e. the maximum displacement region. The reference measurements for the upper and lower tags have been calculated according to the deformation theory, considering the wall as a beam with concentrated load in the middle and constrained with fixed joint and hinge joint. The displacements results have been reported according to the Tags position in rows. The actual displacements detected by the wired transducer (and those calculated for the upper and lower row tags) have been plotted together for reference (figure 6).

As can be observed from the graphs in figure 6, the displacements detected by the Tags during the in situ experimental test are lower than those recorded by the wired transducer. Analyzing the situation in detail, some hypotheses can be advanced. Since it was previously demonstrated that the Tags gave a good response during the laboratory test, and since the geometry, mutual distances and power of the acquisition system have been kept unchanged, the causes of the response anomalies are to be found in the environmental conditions of the experimental set up. For this kind of in situ tests, in fact, the experimental set up requires a metal frame to constraint the wall and to fix the load cell. Moreover, the location of the steel frame necessarily near the metal wall of the building site creates a disadvantage. The high presence of metal has a negative influence on the response of the tags, showing decreased displacements compared to the actual ones. A stronger decrease of displacements is observed for all the tags positioned on the left side of the 3x2 grid (Tag 1.4, 1.3, 1.5), compared to the tags positioned on the right side (Tag 2.1, 1.1, 2.2). This may be due to the presence of the metal wall which, despite being about 140 cm away from the tags, affected the transmission of the signal, modifying the phases and so the distances. Among all the tags, the central row tags 1.3 and 1.1 shows a better response because they are nearer to the antenna. The Displacements detected by the Tags are compared to the calculated displacements detected by the wired transducer.



a) b) c)

Fig. 6. In situ test on the wall: a) Upper row Tag 1.4 and 2.1; b) Central row Tag 1.3 and 1.1; c) Lower row Tag 1.5 and 2.2.

4. Conclusions

In this study, the use of commercial UHF-RFID tags (not embedded in antennas) has been investigated to be employed for civil engineering purposes, specifically for the monitoring of out-of-plane displacements of a brick wall. The innovation of the research is represented by the novelty of the application of commercial tags, usually used in logistic and other purposes, in civil engineering. The feasibility of the application of this technique was assessed by experimental campaigns carried out first in laboratory, then in situ. The experimental set-up of the laboratory campaigns was organized considering the in-situ distances and spaces, to make then a comparison of the results in the same conditions, except for the environment. The laboratory campaigns showed a very good response of the tags. The displacements in fact matched almost perfectly with those imposed. A weaker response of some Tags can be attributed to environmental interference together with the position of the tags with respect to the antenna. Moreover, the intrinsic measurement errors of the reader itself and the errors in processing the received data (standard deviations of the calculated mean values of the phases) should be considered. The response of the Tags in laboratory environment demonstrated to be very satisfactory, proving that the new application of wireless RFID tags for the monitoring of out-of-plane displacements is feasible and potentially very reliable. In situ experiment showed a weaker response of the Tags which registered displacements lower than those recorded by the wired transducer used as reference. The environmental conditions can be supposed to be the causes. The high presence of metal negatively affected the transmission of the electromagnetic signals, modifying the phases and consequently the indirect measures of displacements. Unluckily, the set-up of the in-situ test required a steel frame to constraint the wall and to fix the load cell. Moreover, the position of the experimental set-up necessarily near the metal wall of the building site contributed to negatively affect the displacements results. According to the experimental results, the application of these specific commercial Tags cannot be considered completely reliable, since are strongly affected by the environment conditions. Technology limits related to environment interference can be overcome with the design of new Tags with specific features. Of course, the design of a new tag should guarantee the same advantages of the tags currently available on the market (cost-effectiveness, small size) with better performances regarding the influence of metallic objects and areas in the environment. In conclusion, it can be stated that the application of UHF-RFID tags in civil engineering applications is promising and opens new scenarios for the design of new wireless devices suitable to meet the required needs. The use of this new measurement technology allows the advantage of a wireless, low-cost, non-invasive, and widespread monitoring.

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