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A non-destructive testing methodology for damage assessment of reinforced concrete buildings after seismic events

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ABSTRACT

In the present study non-destructive testing (NDT) methods involving ultrasonic and sonic wave propagation in the solid matter were applied in order to detect and investigate the modifications induced by the seismic load on reinforced concrete (RC) buildings. In particular, the aim of this experimental work was to delineate a methodology for quick and easy application on-the-field to provide information on the state of health of a RC structure subjected to a seismic event by investigating the columns in lower stories, which are generally more safely reachable for inspection. The methodology was experimented through shaking table tests reproducing several earthquakes. Shaking table tests were performed at ENEA Casaccia Research Centre on a full-scale 2-storey RC frame building designed under the current Italian code (NTC2008). Among the considered NDT techniques, direct and indirect sonic methods, as well as partial and complete approaches for ultrasonic tomography application were explored. The above NDTs were applied to the specimen before and after the shaking table testing. Numerical simulations by finite element methods (FEMs) were also adopted for a better comprehension of the dynamic behaviour of the specimen and interpretation of the experimental results. Through the comparison with typical damage indicators formulated for RC buildings, derived from the modal parameters evolution and from the displacements of the structure during the seismic load, promising indications were obtained and the proposed NDT-based methodology was discussed.

1. Introduction

In recent years, innovative non-destructive testing (NDT) techniques, applicable for the assessment of existing civil structures, have become available for in-situ analysis on reinforced concrete (RC) and masonry structures, but they are still not established for regular inspections, especially after seismic events. The damage assessment of RC buildings after seismic events is a very relevant issue in Italy, where most of the constructions built in the last 50 years are RC structures [1].

A wide literature is available on the behaviour of RC buildings under dynamic loads, like seismic actions, and on techniques and methods focused on the localization of damage in the structure [2–7].

In general, both laboratory seismic tests and on-the-field observations after earthquakes show that damages in regular RC frame buildings often concentrate at lower stories and, in particular, at the columns and beam-column joints [8–11].

Large shaking tables capable of generating seismic loads to real-scale specimens are, by now, indispensable tools for laboratory experiments aimed at studying the dynamic behaviour and the evolution of structural damage caused by earthquakes. Thus, the experimental programme involved the reproduction of natural earthquakes by shaking table at ENEA Casaccia Research Centre. The tested specimen was designed under the recent Italian code NTC2008 [12], which was derived from the European EC8 code [13].

In order to detect and investigate the modifications induced by the seismic actions on the building, a NDT experimental campaign was conducted on the RC building before and after the shaking table tests. The applied NDTs were based on ultrasonic and sonic techniques, including tomography, which are methods exploiting the elastic waves propagation through the solid matter that constitutes the structural members. In recent years, NDT techniques and procedures for the assessment of concrete materials have become available and more attractive for on-site use on existing civil structures [14–22]. For example, Masi et al. [23] conducted in-situ NDTs on RC building

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structures, which suffered damage under seismic action, in order to estimate the concrete properties.

Without inducing further damage in the inspected buildings, in fact, NDT can detect internal defects, such as cracking caused by seismic events, which remain hidden from view and compromise the overall integrity of the structure [24]. This capability is due, for the ultrasonic/sonic techniques, to changes in acoustic impedance of concrete, which determine the modification of wave propagation time and, consequently, of the wave velocity. Internal air voids increase the time for a path through the void centre, and so the velocity decreases [25,26]. Velocity decreases as the amount of internal cracking increases [27]. Despite this, the application of such kind of NDTs to structures is still highly demanding on user's skill [28]. Another kind of NDT useful to detect the shape and the distribution of fine cracks in concrete is the X-ray radiography with a contrast medium [22], but the use of this technique can induce safety problems for the personnel at work, so that relevant precaution measures must be taken, such as forbidding the area during acquisitions.

Aim of this experimental study was to explore the possibility of defining a quick and easy procedure for estimating the state of damage of a RC frame structure subjected to a seismic event by the acoustic techniques.

The proposed methodology is intended for slight-to-moderate structural damage condition that is not always easily detectable or quantifiable by visual inspection and, consequently, requires accurate expert evaluation. Moreover, the efficiency and accuracy of visual inspection is often compromised by its subjective nature inherited by the level of expertise of the inspector. This often leads to conservative predictions of the state of the damage of the analysed structure. As a matter of fact, visual inspection is, by definition, subjective and qualitative, so the proposed methodology aims at giving a contribution to relate expert evaluation to objective measurement of the structural damage condition.

2. Experimental tests and surveys

2.1. Reinforced concrete bare frame specimen

A series of shaking table tests were executed on a full-scale 2-storey RC bare frame specimen designed according to NTC2008 code. Fig. 1 illustrates the dimensions of the tested specimen. The weight of the RC bare frame was 15.1 t.

Additional mass loads were located on the first and second floor. In particular, the first floor was loaded with two steel squared plates having dimensions 150 cm × 150 cm and height of 9.5 cm located at the centre of the floor, on top of which other two smaller ones with side of 70 cm and height of 10 cm were bolted. The above mentioned plates were fixed on the first floor with the use of a steel fixture made up of four steel beams derived from U 160 beams with other smaller parts (see Fig. 2 design drawings). A higher mass was located on the first floor of the test frame, as the tested specimen was also used for another research focusing on the study of the behaviour of beam-column nodes. The total added load at the first floor was 4100 kg. Moreover, a 200-kg steel plate was also fixed at each corner of the second floor, reaching an overall additional load of 800 kg. Consequently, the weight of the loaded specimen was 20.0 t. In Fig. 3 the specimen positioned on the shaking table is shown.

2.2. FEM and operational modal analyses

A preliminary numerical model of the specimen was created by finite elements (FE) in order to perform numerical analyses. Contemporarily, before locating the additional mass loads on the specimen, ambient vibration data were acquired and processed by operational modal analysis (OMA) techniques. On the one hand, numerical modal analysis by FE provided indications to define the most proper positions where to place the sensors for experimental data acquisition. On the other hand, OMA results were used to calibrate the finite element model (FEM) and to confirm the preliminary assumptions on material properties and boundary conditions.

The FEM geometry was based on computer-aided design (CAD) drawings. The model was made up of 19,412 nodes and 12,828 hexa elements. As for the boundary conditions, it was assumed attached to the ground, since it simulated the specimen tightened to the shaking table. The following materials properties were considered: density was 2500 kg/m^3, Poisson's coefficient was 0.2 and Young's modulus was 3E + 10 Pa. The total weight of the structure was 14.2 t. In Fig. 4 the FEM mesh and the centre of gravity (whose coordinates are x = 1.749 m, y = 1.501 m and z = 2.775 m) are depicted.

Subsequently, the model was updated by the average values of density and Young's Modulus obtained through non-destructive and destructive tests performed on 5 different cast concrete specimens. The numerical modal analysis was performed by Nastran code. The results in terms of modal shapes are shown in Fig. 5. The participating mass resulted 63.2% along x for the 1st mode, 63.3% along y for the 2nd mode.

The OMA was carried out with ambient vibration data acquired by triaxial velocimeters placed at the measurement points indicated by the arrows in Fig. 6. In particular, the frequency domain decomposition (FDD) technique was utilised. In Fig. 6(a)–(c) the modal shapes of the first three modes are depicted. The identification of the first three modal frequencies by preliminary OMA is illustrated in Fig. 7.

The effect of the additional mass was estimated to lower the first two modal frequencies (bending mode in x and y directions, respectively) of about 2 Hz.

The numerical results were compared with in situ environmental vibration measures obtained by three seismographs (SARA Instruments), data were acquired in three different configurations above described equipped with 0.2 Hz triaxial electrodynamic velocimeters, were set to 200 Hz sampling frequency. The experimental and numerical data are summarized in Table 1.

A FEM was also used to estimate the strain and the bending moments of the specimen in static conditions and under seismic load. In particular, the seismic load was simulated considering the L'Aquila earthquake, Italy, 2009, recorded at AQV seismic station near Pettino neighbourhood. Figs. 8(b) and 9(b) show the results of the simulation with the seismic input scaled at 150% of PGA compared to the results in static conditions (Figs. 8(a) and 9(a)).

2.3. Shaking table tests and DySCO virtual laboratory

The shaking table tests were carried out at the ENEA Casaccia Research Centre. The main technical specifications of the used shaking tables are summarized in Table 2.

The specimen was subjected to a sequence of seismic inputs chosen among the main Italian and international earthquakes of the last 40 years that have the highest damaging potential with reference to the studied specimen. The Velocity Spectrum Intensity (VSI) calculated in the frequency range 4–7 Hz (natural frequencies of the undamaged specimen with the additional mass loads, according to preliminary modal analyses) was considered as an indicator of the seismic input damaging potential. An artificial earthquake was also considered. It was calculated according to IEEE344 standard. The selected natural seismic inputs were: Gilroy (Loma Prieta earthquake, California 1989), Colfiorito (Umbria-Marche earthquake, Italy 1997), Mirandola (Emila-Romagna earthquake, Italy 2012), Aquila (L'Aquila earthquake, Italy 2009), Pettino (L'Aquila earthquake, Italy 2009) and Tabas (Tabas earthquake, Iran 1978). All the above-mentioned inputs were initially scaled at 25% of Peak Ground Acceleration (PGA) and gradually increased by 25% of PGA each step. Each step was alternated with a random test (white noise input) at low intensity (0.05 g of PGA) for dynamic identification of the specimen. After a total amount of 16