Critical evaluation of NDT for rapid condition assessment of existing RC buildings: A case study

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Abstract. There is an urgent need for rapid and reliable condition assessment of existing reinforced concrete (RC) buildings as a basis for structural safety evaluation, especially in developing countries in seismic regions such as Turkey. Traditionally, RC structures are evaluated by taking core samples from a limited number of structural elements for concrete strength and performing spot checks for the steel reinforcement by removing the concrete cover. In-situ concrete strength is determined through compression testing of core samples. Through spot checks, conformance of the existing reinforcement with the structural drawings is evaluated and a reinforcement realization factor is calculated for use in the analyses. Even though these conventional methods are relatively more accurate and reliable for condition assessment of existing RC structures, they are destructive, involved, time taking, slow and expensive. Non-destructive testing (NDT) methods are proposed as a solution to this problem. Using NDT methods in conjunction with a relatively small number of core tests potentially allows for more rapid yet still reliable condition assessment of existing structures. In this paper, a critical evaluation of rapid and reliable condition assessment methods is made through investigations on an 18-story residential RC building as a case study. Investigation results show that using NDT helps achieve time and cost savings while allowing for reliable condition assessment of existing buildings, and promises further savings through continued research and development in this area.

1 Introduction

NDT methods that enable quick and reliable property measurement and feature detection without significant damage to the structure are urgently needed for rapid and reliable condition assessment of large building stocks in seismic regions [1]. Condition assessment of RC buildings mainly consists of in-situ concrete strength determination and conformance verification of steel reinforcement areas and details to structural drawings. The compressive strength of concrete is often given priority since it is an essential mechanical property that is also indicative of the overall material and construction quality [2,3]. The most widely used procedure for the determination of concrete compressive strength is taking core samples from structures [4]. Uniaxial compressive strength tests are conducted on the core samples to determine concrete strength. Although this traditional method provides highly reliable results, it is destructive, difficult, slow and expensive [5]. NDT methods stand out with their significant time and cost savings potential in estimation of in-situ concrete strength. When sampled sensibly, they do not cause significant structural or functional damage to the building elements. NDT methods measure various properties of concrete that can be indirectly correlated with its compressive strength. NDT measurements obtained from a limited number of elements are used to build regression models to predict compressive strength of concrete elsewhere within the structure based on NDT results within a certain margin of error. The reliability of concrete strength estimation can be influenced by various parameters. By combining different NDT methods, some of these effects can be minimized [6]. Hence, the reliability of strength prediction can be improved and more accurate in-situ strength estimation can be made by combining two or more NDT techniques [7-10].

The investigations presented in this paper focused on using various NDT methods to improve the speed, accuracy and reliability of the condition assessment of an existing RC building. while limiting the number of core samples and concrete cover removal. A high-end radar detector was used for steel reinforcement detection and sizing for verification of conformance to available structural drawings. Three NDT methods, namely rebound (Schmidt) hammer, ultrasonic pulse velocity (UPV), and drilling resistance were used for estimation of in-situ concrete strength. The case study building investigated in this study is a relatively new residential building constructed with good quality materials and workmanship in an upscale neighbourhood. Hence, a main objective was to inflict minimum damage to the structure and cause minimum discomfort to the occupants while performing the investigations without significantly compromising the accuracy and reliability of the condition assessment and seismic safety evaluation. Therefore, all destructive investigations were limited to the basement and ground floors of the building, and only NDT investigations were carried out in the upper floors.

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2 Building Information

The case-study residential building shown in Fig. 1 is located in Istanbul, Turkey, and it was constructed in 1994-1997 before the Kocaeli Earthquake (M_w 7.4) in 1999 and the subsequent seismic code updates in 2007 and 2018. The building has two basement floors, ground floor and 15 upper floors with an attic at the top floor, hence 18 floors in total. The building has a closed parking garage and a swimming pool in the second basement that are built integral to the building, without expansion joints, but outside the plan dimensions of the upper floors. Plan dimensions of a typical upper floor shown in Fig. 2 are 24.25x12.10 m and the floor heights are 2.7 m in the second basement floor, 2.8 m in the first basement floor, 4.0 m in the ground floor and 2.9 m in the upper floors. The total building height is 51.40 m from ground level and 55.90 m including the basement floors. The structural system of the building is an RC frame with shear walls as shown in Fig. 2. The foundation system of the building is mat foundation within the plan dimensions and individual footings with grade beams under the parking garage. The slab system is formed by 12 cm slabs and 30x50 cm beams on the second basement, 15 cm slabs and 30x60 cm beams on the first basement and 30 cm thick joist slabs on the ground and upper floors. St III (S420) class deformed steel bars and B225 (C18) class concrete were specified on the structural drawings for the building.

Fig. 1. Case-study residential building in Istanbul, Turkey

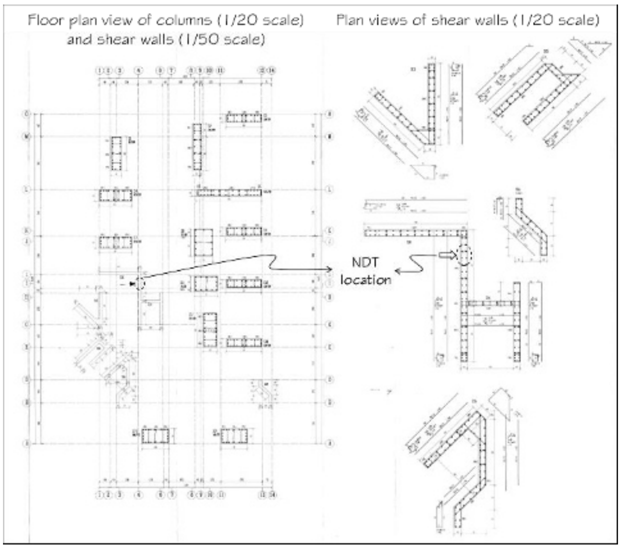

Fig. 2. Plan views of columns and shear walls on a typical upper floor (indicated scales are on actual structural drawings), also showing the concrete NDT location on floors 1-15

3 Methodology

The current seismic code in Turkey that was enacted in 2018 [11] requires that based on the structural information available during the condition assessment of existing RC buildings, 2-3 concrete cores shall be taken on each floor to determine the existing concrete strength, and reinforcement spot checks shall be performed in 5-10% of the columns or shear walls on each floor by removing the concrete cover. An alternative approach was taken in this study where strict compliance with the seismic code was not sought after. Considering that the structural drawings are available for the case-study building, the construction quality is high, and that there is a single residence on each upper floor, a single location was identified on each upper floor on the shear wall surrounding the staircase for NDT investigations only. The NDT location is shown on the floor plan in Fig. 2 and a photo of the test location is shown in Fig. 3, where the plaster is removed at two areas approximately 30-40 cm apart using a 10 cm diameter concrete punch mounted on a drill to expose the concrete surface for NDT applications.

Fig. 3. Concrete NDT test location (see Fig. 2) on floors 1-15

Schmidt hammer, UPV and drilling resistance tests were performed on the NDT areas (Fig. 3) at the same location (Fig. 2) on each upper floor of the building. NDT locations were scanned for rebars before removing the plaster in order to centre the test areas within the reinforcement grid as shown in Fig. 3. Hence, three 10 mm diameter holes of 10 cm length drilled in each test area in Fig. 3 constitute the whole damage inflicted on the upper floors during the condition assessment work in the building. All destructive investigations were carried out on the ground and two basement floors in conjunction with NDT methods in order to obtain the relationships between the NDT and core test results. A total of 9 concrete cores were taken, 3 from each floor, in compliance with EN 13791 [12] and all three NDT methods were also applied at each core location in order to perform correlation studies. In addition, all accessible columns and shear walls in the ground and two basement floors were scanned using the radar detector to check and verify the conformance of steel reinforcement to the structural drawings. When in doubt, concrete cover was removed for visual inspection of the reinforcement. Once it was verified that the reinforcement details conformed to the structural drawings, no additional reinforcement scans were performed in the upper floors in order not to disturb the occupants.

3.1 NDT and Investigations

Three NDT methods, namely Schmidt hammer [13], UPV [14], and drilling resistance [15,16] were conducted for in-situ concrete strength estimation at NDT locations on all upper floors (Figs 2 and 3) as well as at core locations on the ground and two basement floors. Fig. 4a shows an indirect (same surface) UPV measurement conducted at NDT locations. A fixed distance was used between the transducers due to limited access to concrete surface.

a b

Fig. 4. (a) Indirect UPV tests at NDT locations in the building; b) direct UPV tests on concrete cores in the laboratory

Direct (opposite face) UPV measurements were also conducted in the laboratory on the core samples as shown in Fig. 4b for comparison with the on-site indirect measurements.

In-situ concrete strength estimation using a drilling resistance method was developed through a comprehensive experimental research project conducted at ITU and funded by the Scientific and Technological Research Council of Turkey (TUBITAK Grant No: 214M054). Fig. 5 shows the application of the drilling resistance method at an NDT location, which involves drilling three 10 mm diameter holes of 10 cm length at each test area using a drill instrumented with a linear potentiometer to measure the drilling depth vs. time. The potentiometer is connected to a dynamic data acquisition system shown in Fig. 3 and the drilling depth-time data shown in Fig. 6 is stored in a computer from which the drilling resistance can be calculated as an instantaneous or average value based on the slope.

Fig. 5. Drilling resistance test at NDT locations on floors 1-15

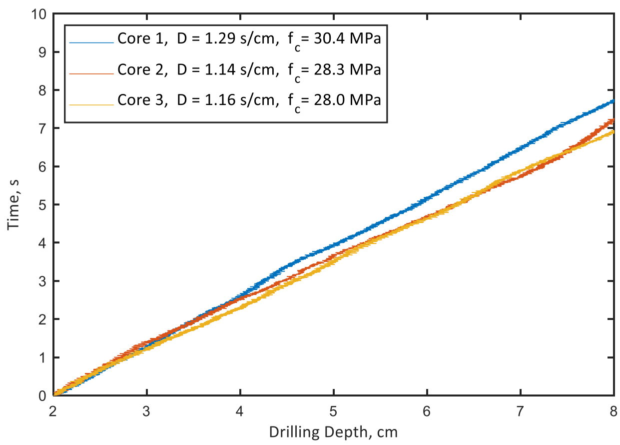

Fig. 6. Sample drilling resistance data obtained at test locations where core results are also available.

Fig. 6 shows sample drilling/depth-time data obtained from three locations on the second basement floor where core samples were also taken. Although 10 cm long holes were drilled, data from the first and last 2 cm were excluded to obtain more uniform data that is less affected by near surface conditions as well as the anomalies at the beginning and end of drilling. Also, contrary to common practice, the drilling depth-time data are drawn on the x- and y-axes, respectively, so that the slope of the curve is proportional to drilling resistance, and hence the concrete strength. The slopes of the lines fitted to the curves in Fig. 6, i.e. the drilling resistance values are related to the concrete core test results provided in the legend such that higher slope means higher concrete strength.

In addition to concrete NDT for estimation of strength, non-destructive detection and sizing of steel reinforcement was performed for all accessible columns and shear walls on the ground and two basement floors. A high-end radar scanner was used for this purpose, which sends electromagnetic impulse waves into the concrete element and processes the reflected signals to reconstruct an image of the element's interior. Fig. 7 shows typical scanning of a column element for longitudinal and transverse reinforcement detection and sizing. Typical output of the scanner is shown in Fig. 8, providing pictorial views of the longitudinal (vertical) and transverse (horizontal) reinforcement as well as the concrete cover thickness in each direction. The scan report also provides estimated sizes of both longitudinal and transverse reinforcement.

The main objective of performing non-destructive detection and sizing of reinforcement in all accessible columns and shear walls on the ground and two basement floors was to verify conformance of reinforcement details to the available structural drawings. Once such conformance is verified, scanning of structural elements in the upper floors could be avoided since it would require access to the residences. While the reinforcement scanner shown in Fig. 7 provides successful results such as in Fig. 8 in most cases, false detection or misdetection of reinforcement is possible as also evident in Fig. 8. If the rebar scans on the lower floors do not establish conformance to structural drawings, then additional scans are necessary on the upper floors to determine the discrepancies in reinforcement areas and the associated reinforcement realization ratios for use in the analyses.

Rebar scans on the ground and two basement floors of the case study building generally revealed conformance to the structural drawings with a limited number of exceptions. The most notable exception was in the case of column S7 on the second basement floor. According to the structural drawings, this column has 20ϕ22 and 8ϕ14 longitudinal reinforcement bars, but the rebar scan detected 16ϕ22 and 6ϕ14, which corresponds to 20.7% lower reinforcement area and a reinforcement realization factor of 0.793. Hence, visual inspection of the reinforcement in this column was deemed necessary by removing the concrete cover as described in the following section.

Fig. 7. Detection and sizing of column reinforcement using a high-end radar detector

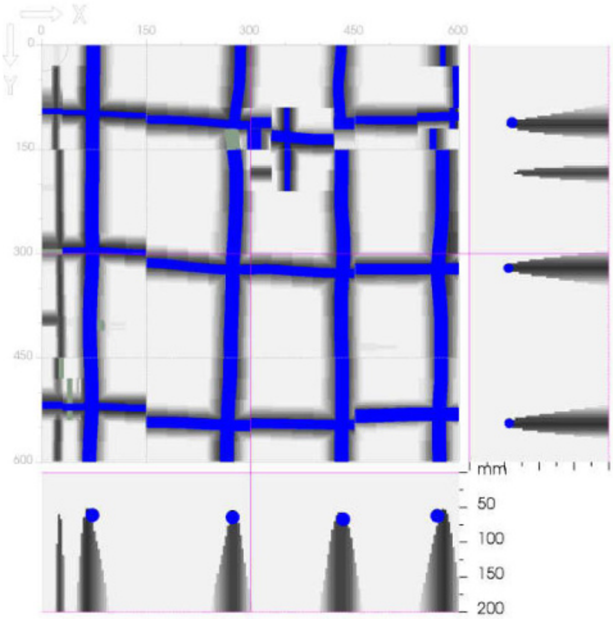

Fig. 8. Sample output of column reinforcement scanning

3.2 Destructive Testing and Investigations

Conventional core sampling constitutes the main destructive testing in condition assessment of existing buildings. A total of 9 concrete core samples were taken from the ground and two basement floors of the investigated building in compliance with TS EN 13791 and TS EN 12504-1 [17]. The NDT methods described in the previous section were also performed at each core location in order to develop the relationships needed for evaluation of the NDT results obtained from the upper floors. Fig. 9 shows compression testing of cores and the core samples taken from the building. The core samples were first cut to a length approximately equal to its diameter in accordance with the Turkish Seismic Code.

Fig. 9. (a) Compression testing or cores; (b) core samples

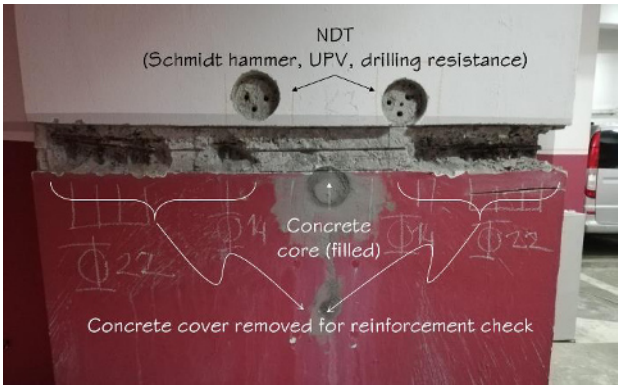

Fig. 10. Column S7 on the second basement floor

Prior to capping of the cores for compression testing, direct UPV tests were performed on each core (Fig. 4b) according to TS EN 12504-4 [14] for comparison with the on-site indirect UPV test results (Fig. 4a).

Fig. 10 shows column S7 on the second basement floor where core sampling, NDT and cover concrete removal were performed. Visual inspection of the column reinforcement revealed conformance to the structural drawings despite the discrepancy reported by the previous reinforcement scan. Hence, no further reinforcement scanning was performed on the upper floors.

4 Results and Discussions

Figs. 11-14 show the relationships obtained between NDT and core test results obtained from the ground and two basement floors as well as the NDT results obtained from the upper floors. The relationships obtained through regression are plotted as a solid line and the corresponding equations are given in the figure legends. NDT results obtained from the upper floors are shown in red on the same figure for comparison of the range of NDT results.

Similarly, Tables 1 and 2 show the NDT and core test results obtained from respective floors. Statistical descriptive values and estimations based on NDT and destructive investigations are also provided in the tables.

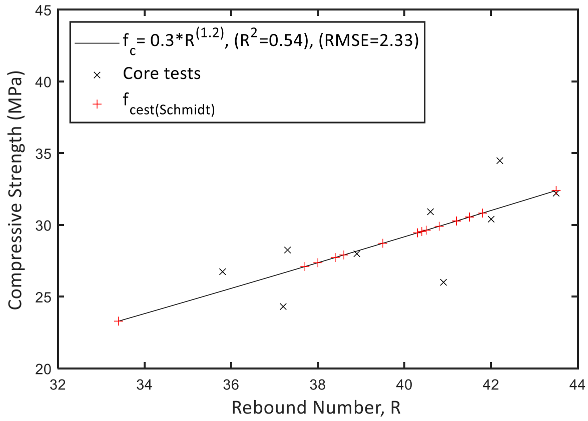

Fig. 11. Schmidt hammer and core test results

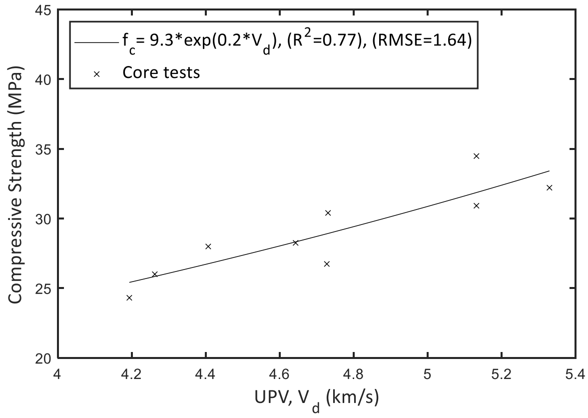

Fig. 12. Direct-UPV and core test results

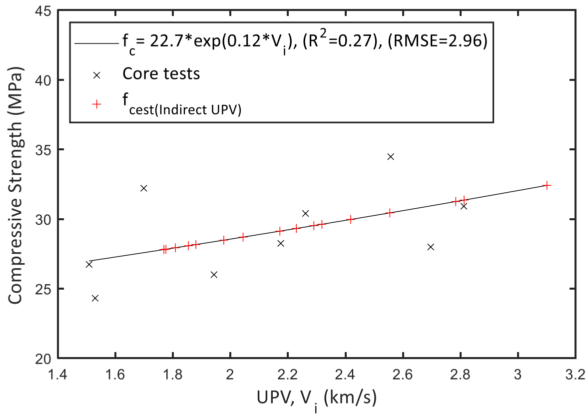

Fig. 13. Indirect-UPV and core test results

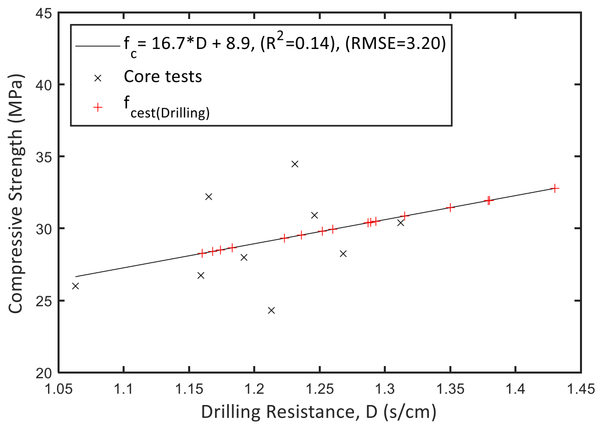

Fig. 14. Drilling resistance and core test results

Table 1. NDT and compressive strength test results at core locations

Story	Core	Drilling Resistance (s/cm)	UPV_{ind} (km/s)	Rebound Number	UPV_{direct} (km/s)*	Compressive Strength (MPa)
-2	1	1,312	2,261	42,0	4,731	30,4
-2	2	1,268	2,175	37,3	4,643	28,3
-2	3	1,192	2,696	38,9	4,407	28,0
-1	4	1,210	1,509	35,8	4,727	26,7
-1	5	1,305	2,557	42,2	5,132	34,5
-1	6	1,400	2,811	40,6	5,132	30,9
G	7	1,213	1,530	37,2	4,194	24,3
G	8	1,114	1,943	40,9	4,262	26,0
G	9	1,165	1,699	43,5	5,329	32,2
Mean		**1,239**	**2,131**	**39,8**	**4,728**	**29,0**
St. Dev.		**0,102**	**0,494**	**2,6**	**0,403**	**3,2**
In-situ concrete strength = max[(mean – st. dev.), (0.85xmean)] (TSC, 2018)						**25.8 MPa (C25)**

*Tests were conducted on core samples in the laboratory.

Table 2. NDT results and compressive strength estimation based on NDT results

Story	UPV_{ind} (km/s)	Drilling Resistance (s/cm)	Rebound Number	fc_{est} (UPV_{ind}) (MPa)	fc_{est} (Schmidt) (MPa)	fc_{est} (UPV_{ind}+ Schmidt) (MPa)	fc_{est} (Drilling) (MPa)	fc_{est} (Drilling+ Schmidt) (MPa)	fc_{est} (Drilling+ UPV_{ind}) (MPa)	fc_{est} (Drilling+ Schmidt+ UPV_{ind}) (MPa)
15	1,854	1,430	39,5	28,1	28,7	28,2	32,8	32,3	30,2	31,3
14	1,977	1,252	40,8	28,5	29,9	29,5	29,8	30,6	29,0	30,2
13	2,229	1,293	40,4	29,3	29,5	29,7	30,5	30,9	30,1	30,7
12	1,809	1,174	38,6	27,9	27,9	27,4	28,5	27,5	27,8	27,3
11	1,769	1,183	41,2	27,8	30,3	29,4	28,7	29,9	27,8	29,4
10	1,880	1,289	40,5	28,2	29,6	29,0	30,4	31,0	29,0	30,3
9	2,554	1,350	41,8	30,4	30,8	31,4	31,4	33,1	31,5	33,0
8	2,783	1,379	38,0	31,3	27,4	28,9	31,9	30,2	32,4	30,5
7	2,172	1,380	40,3	29,1	29,5	29,5	32,0	32,2	30,7	31,7
6	2,418	1,236	41,5	30,0	30,5	30,9	29,5	31,0	30,1	31,1
5	1,776	1,287	33,4	27,8	23,3	23,4	30,4	24,6	28,7	24,4
4	2,044	1,315	37,7	28,7	27,1	27,2	30,9	28,9	29,7	28,6
3	2,318	1,223	43,5	29,6	32,4	32,2	29,3	32,6	29,7	32,5
2	2,290	1,168	41,2	29,5	30,3	30,4	28,4	29,7	29,2	29,9
1	2,812	1,260	41,5	31,4	30,6	31,7	29,9	31,4	31,5	31,9
Z	3,100	1,160	38,4	32,4	27,8	29,9	28,3	27,1	31,4	28,5
Mean	**2,237**	**1,274**	**39,9**	**29,4**	**29,1**	**29,3**	**30,2**	**30,2**	**29,9**	**30,1**
St. Dev.	**0,409**	**0,083**	**2,3**	**1,4**	**2,1**	**2,1**	**1,4**	**2,3**	**1,3**	**2,1**

Fairly satisfactory relationships and correlations were obtained in Figs. 11-14 considering the limited core test data. Although the coefficient of determination values (R^2) are low, the data trends are clear and the RMSE values are sufficiently low to allow satisfactory evaluation of NDT results. The NDT results obtained from the upper floors generally fall within the range of the NDT-core test results with a single exception in Fig. 11 in which an unusually low rebound number value was obtained on the 5th floor. However, this observation was not supported by either UPV or drilling resistance test results. Hence, it was not deemed necessary to drill a core sample on the fifth floor. As a result, the strategy adopted for the case study building allowed for satisfactorily accurate and reliable condition assessment of the building without any significant damage to the building or any significant discomfort to the occupants in the upper floor residences.

The case study building presented in this paper was designed according to the 1975 version of the Turkish Seismic Code. The design documents of the building specify B225 (C18) concrete strength class and St III (S420) steel reinforcement class. Based on the core test results provided in Table 1, the existing (in-situ) concrete strength was calculated as 25.8 MPa or C25 strength class according to the current seismic code. Hence, the in-situ concrete strength in the building satisfies the current seismic code [11] which requires a minimum of C25 strength class for concrete. The properties of the existing steel reinforcement also conform to the current seismic code and reinforcing steel standard TS 708 [18] to a large extent.

The provisions of Turkish Seismic Code dated 1975 lack the ductile design principles of the current seismic code, especially with regard to the confinement zones of columns and beams as well as special seismic transverse reinforcement details. Hence, seismic safety evaluation of the building needs to be performed according to the provisions of the current seismic code. It should be noted, however, that the buildings designed and constructed in compliance with the seismic code in effect during their construction generally displayed satisfactory performance during past major earthquakes. Seismic safety evaluation of the case study building according to the current seismic code is currently in progress and the results will be published elsewhere as an extended version of this paper.

5 Conclusions

In this paper, the use of NDT methods for rapid and reliable condition assessment of a case study building in Istanbul, Turkey was investigated. Three concrete NDT methods were correlated with the test results on concrete cores taken from the ground and two basement floors of the 18-story building. Only NDT methods were implemented on the upper floors, the results of which were evaluated using the correlations established between the NDT and core tests results. Conformance of the reinforcement areas in columns and shear walls to the structural drawings was established through non-destructive scanning of reinforcement using a high-end radar detector. Despite limited detection problems encountered with the reinforcement scanner and relatively high scatter in the NDT data resulting in low coefficient of determination values, the adopted strategy allowed for sufficiently accurate and reliable condition assessment of the case study building without inflicting any significant damage or causing any significant occupant discomfort in the upper floors.

Continued research and development is needed in the areas of decreasing the variability and scatter in the NDT results, particularly in the indirect UPV and drilling resistance methods, and developing more accurate reinforcement detectors or more efficient means of concrete cover removal for visual inspection of the steel reinforcement.

It should be noted that the success of the condition assessment work performed in this study is to a large extent due to the case study building's high-quality materials and workmanship, not to mention the availability of structural drawings and conformance of construction to the structural drawings.

Seismic safety evaluation of the case study building according to the current seismic code is currently underway and the results will be shared in a future extended publication that also will include the potential effects of variability in NDT results on the seismic performance level.

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References

1. Gunes, O. (2015), Turkey's grand challenge: Disaster-proof building inventory within 20 years, Case Studies in Construction Materials, 2, 18-34.
2. Neville, A.M. (2011) Properties of Concrete. 5th Edition, Longman, England.
3. Pucinotti, R. (2013). Assessment of in situ characteristic concrete strength. Construction and Building Materials, 44, 63-73.
4. Malhotra, V. M., & Carino, N. J. (2003). Handbook on non-destructive testing of concrete. CRC press.
5. Soutsos, M. N., Breysse, D., Garnier, V., Goncalves, A., and Monteiro, A. V. (2012). Estimation of on-site compressive strength of concrete. In Non-Destructive Assessment of Concrete Structures: Reliability and Limits of Single and Combined Techniques, pp. 119-186, Springer, Dordrecht.
6. Pucinotti, R. (2015). Reinforced concrete structure: Non-destructive in situ strength assessment of

concrete. Construction and Building Materials, 75, 331-341.

7. Breysse, D. (2012a), Non-destructive evaluation of concrete strength: An historical review and a new perspective by combining NDT methods, Construction and Building Materials, 33, 139-163.
8. Breysse, D. (Ed.). (2012b). Non-destructive assessment of concrete structures: Reliability and limits of single and combined techniques: State-of-the-art report of the RILEM technical committee 207-INR (Vol. 1). Springer Science & Business Media.
9. Breysse, D. and Balayssac, J.P. (Eds) (2021), Non-destructive in situ strength assessment of concrete. Springer International Publishing.
10. Breysse, D., Balayssac, J.-P., Alwash, M., Biondi, S., Chiauzzi, L., Corbett, D., Garnier, V., Gonçalves, A., Grantham, M., Gunes, O., Kenaï, S., Luprano, V.A.M., Masi, A., Moczko, A., Qasrawi, H.Y., Romão, X., Sbartaï, Z.M., Monteiro, A.V., and Vasanelli, E. (2021), In-Situ Strength Assessment of Concrete: Detailed Guidelines, Non-Destructive In Situ Strength Assessment of Concrete, pp. 3-56, Springer.
11. TSC (2018), Essentials for Design of Buildings under Earthquake Effects, Disaster and Emergency Management Directorate, Ankara.
12. EN 13791 (2019), Assessment of in-situ compressive strength in structures and precast concrete components, European Committee for Standardization, Brussels.
13. EN 12504-2:2021. Testing concrete in structures - Part 2: Non-destructive testing - Determination of rebound number, European Committee for Standardization, Brussels.
14. EN 12504-4:2021. Testing concrete in structures - Part 4: Determination of ultrasonic pulse velocity, European Committee for Standardization, Brussels.
15. S. Karatosun (2021), Estimation of in-situ concrete strength using drilling resistance method and machine learning, M.Sc. Thesis, Istanbul Technical University, Istanbul, Turkey.
16. Karatosun, S., Asan, M., and Gunes, O. (2019). Estimation of In-situ concrete strength using drilling resistance. In MATEC Web of Conferences (Vol. 289, p. 06001). EDP Sciences.
17. EN 12504-1 (2021), Testing concrete in structures - Part 1: Cored specimens - Taking, examining and testing in compression, European Committee for Standardization, Brussels.
18. TS 708 (2010), Steel for the reinforcement of concrete - Reinforcing steel, Turkish Standards Institute, Ankara.