International Journal of GEOMATE, Oct., 2022, Vol.23, Issue 98, pp.117-124
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2022.98.3540
Geotechnique, Construction Materials and Environment

VERIFICATION OF DESIGN BEARING CAPACITY OF EXISTING REINFORCED CONCRETE COLUMNS

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*Corresponding Author, Received: 02 Aug. 2022, Revised: 09 Sept. 2022, Accepted: 10 Oct. 2022

ABSTRACT: Most of the case studies reported in the literature on rebound hammer testing focus on the assessment of the compressive strength of concrete. The objective of this paper is to extend the use of rebound hammer data to assess the overall bearing capacity of existing reinforced concrete columns subject to combined compression and bending. This research concentrates on typical columns of two buildings under construction, with site-mixed concrete used for one building and ready-mixed concrete used for the other. Concrete specimens were taken from the construction sites for rebound hammer test and compression test whereby a correlation between the rebound index and concrete strength was developed. On-site rebound hammer tests were then performed on the columns to estimate the in-place concrete strength using the correlation established previously. In addition, the actual strength of reinforcement was determined via tensile testing of reinforcement specimens. Compared with the site-mixed concrete, the ready-mixed concrete exhibited an 18% lower coefficient of variation in strength. The in-place concrete strength was 24-31% greater than the standardized concrete strength. The moment-axial load interaction diagrams of the columns were calculated based on the determined strengths of concrete and steel reinforcement. It was found that the actual bearing capacity in combined compression and bending of the existing columns was 34-47% greater than the design bearing capacity. The proposed non-invasive procedure successfully verified the design strength of the surveyed columns. However, using only one non-destructive test method to estimate the concrete strength may somewhat limit the accuracy of the prediction.

Keywords: Concrete column, Compressive strength, Rebound hammer, Correlation, Interaction diagram

1. INTRODUCTION

Non-destructive test (NDT) methods are being used in construction industry for quality control in new construction, troubleshooting of problems, condition assessment of existing structures as well as quality assurance of repair works. NDT methods can provide essential information on the performance of reinforced concrete (RC) structures such as concrete strength, location of cracking, delamination, and debonding, location, size, and corrosion activity of steel reinforcement [1]. The advantages, limitations and interpretations, and potential of commonly used NDT methods were reviewed in [2]. The rebound hammer test measures the hardness of the concrete surface, thereby estimating the strength of the concrete. The rebound number reveals the proportion of the energy returned to the hammer after striking the surface of the concrete. The ultrasonic pulse velocity (UPV) test is based on measuring the speed of ultrasonic waves traveling in concrete to estimate the strength and predict the crack depth of concrete.

NDT could provide useful data for maintenance, repair, and renovation work, especially when signs of deterioration such as cracking, and corrosion are observed on RC buildings [3,4]. Adnan combined UPV and rebound hammer tests to evaluate the concrete strength of 38 columns and 29 ground beams of an old mosque [5]. Yaqub and Bailey performed UPV tests on undamaged and heat-damaged concrete columns to evaluate the residual strength of post-heated RC columns [6]. Venkatesh and Alapati conducted UPV, rebound hammer and half-cell potential tests on RC columns, beams and slabs of a 50-year old hospital building in India to assess the strength and durability of concrete and the corrosion status of reinforcing bars [7]. Sanchez et al. used observation data from rebound hammer tests on a RC bridge beam to update a probabilistic prediction of flexural failure of the beam due to carbonation [8]. Concha and Oreta utilized data acquired from UPV testing of concrete specimens to develop a neural network model for the prediction of the bond strength of rebars in concrete structures [9]. Using a rebound hammer together with UPV and compression tests, Qasrawi observed variation in strength among concrete cores taken from different positions along column length [10]. Asteris and Mokos developed artificial neural network models for the prediction of the compressive strength of concrete from the rebound hammer and UPV measurements [11].

The rebound hammer (also known as the Schmidt hammer) test, which is one of the most popular NDT methods, is codified in many technical standards [12-15]. Being simple and convenient for field applications, the rebound hammer test can be used to estimate the concrete strength of in-use building structures without sampling [16]. The Vietnamese standard on rebound hammer test TCVN 9334:2012 recommends developing correlations between the rebound index and the concrete strength based on concrete specimens made from the same materials as the concrete of the structure to be tested [15]. Factors affecting the performance of rebound hammer may include the water-cement ratio, carbonation, moisture content, surface condition, compaction, curing condition, specimen size, exposure to fire and cement type [17,18]. Sanchez and Tarranza found that the average rebound number for concrete cube specimens immersed in brackish water was considerably lower than that for specimens under normal room conditions [19]. Benyahia et al. observed a significant difference between core compression tests and rebound hammer tests using correlations introduced by the equipment manufacturer, hence the need for developing correlations based on local environmental and material conditions [20]. Panedpojaman and Tonnayopas found that after heating, the decrease in concrete strength was much clearer than the degradation of rebound index [21]. Brencich et al. noticed the dependence of the rebound hammer result on the moisture content, specimen mass, boundary conditions and stress state [22]. While most of the case studies reported in the literature on rebound hammer testing focus on the assessment of compressive strength of concrete, this paper extends the use of rebound hammer data to assess the overall bearing capacity of structural members subject to combined bending and compression.

2. RESEARCH SIGNIFICANCE

Since columns are critical structural members in a building, it can be risky to extract concrete cores for laboratory testing. This paper discusses a possible approach to combine the rebound hammer test with other experimental and computational methods for non-invasive evaluation of the combined compression and bending strength of existing RC columns. Specifically, the concrete strength estimated from the rebound hammer test and the reinforcement strength determined from the reinforcement tensile test are used to build the interaction diagrams that represent the moment and axial capacities of some RC columns in two buildings under construction. The in-place bearing capacity of the columns is then checked against the design bearing capacity based on standardized material properties. Moreover, the findings related to site-mixed concrete are compared with those related to ready-mixed concrete.

3. MATERIALS AND METHODS

3.1 Case Study Columns

The investigated columns were located on the first story of two low-rise buildings under construction in a suburb of Vietnam. The first building was a primary school where the concrete was mixed on-site and manually poured. The second building was a government office building where the columns were cast with ready-mixed concrete. The first building's columns were designed for compression and bending following the Vietnamese concrete design standard TCVN 5574:2018 [23], using B15 grade concrete (15 MPa characteristic compressive strength) and steel reinforcement with a standardized yield strength of 300 MPa. The second building's columns were designed for compression and bending using B20 grade concrete and 300 MPa steel reinforcement. Fig.1 shows the cross-sectional dimensions and reinforcement distribution of the columns.

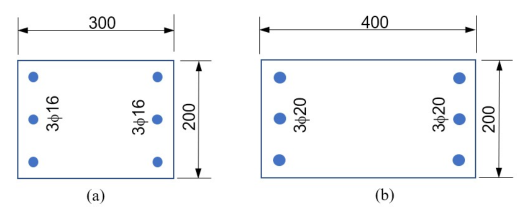

Fig.1 Cross-sectional details of columns of (a) building 1, (b) building 2

The following tasks were conducted to evaluate the in-place bearing capacity of the case study columns: (i) Determine the correlation between rebound number and concrete strength based on rebound hammer testing and direct compression testing of concrete specimens; (ii) Determine the reinforcement yield strength based on tensile testing of steel reinforcement specimens; (iii) Estimate the strength of concrete in the columns via on-site rebound hammer tests; (iv) Calculate interaction diagrams to represent the columns bearing capacity in combined bending and compression.

3.2 Testing of Material Specimens

The compressive strength of the concrete of the columns can be estimated on the basis of the preconstructed experimental relationship between the rebound index read from the rebound hammer and the compressive strength acquired from the compression testing machine for the same specimen group. It was hence necessary to first establish a relationship between the concrete compressive strength f_c and the rebound number n for each concrete strength grade (B15 and B20) using experimental data of 20 specimen groups with 3 specimens each. The standard specimens according to the Vietnamese codes were 150x150x150 mm cubes [15]. Fig.2 shows a typical three-gang cube mold used to collect 3 concrete specimens at the construction site. The specimens had the same mix ratio, age and curing condition as the concrete in the investigated columns.

Using an N-type classic Schmidt rebound hammer with an impact energy of 2.207 Nm, the rebound test was carried out horizontally with the concrete specimen fixed on a testing machine under a compressive pressure of 0.5 MPa as shown in Fig.3. Following TCVN 9334:2012 [15], the impact points were at least 30 mm from the edge of the specimen and 30 mm apart. Each sample was tested for 16 points, removed 3 maximum readings and 3 minimum readings, and averaged the remaining 10 readings. Similarly, the British standard BS EN 12504-2:2021 recommends taking at least 9 readings for a test location in which no two impact points are closer than 25 mm [14].

Fig.2 Making on-site concrete specimens

Fig.3 Rebound hammer test of concrete cube

After being tested with the rebound hammer, the specimen was placed in a compression testing machine to find the corresponding compressive strength. Using a TYA-2000 compression testing machine with a maximum capacity of 2000 kN (Fig.4), load was applied gradually at the rate of 0.5 MPa per second until the specimen failed at which the compressive strength was identified [24].

Fig.4 Compression test of concrete cube

Let n_i and $f_{c,\,i}$ be the average rebound number and compressive strength, respectively, obtained for the i-th concrete specimen group. For a concrete strength grade, when the range of the measured strength fluctuates up to 20 MPa, the f_c-n relationship can be characterized by a linear regression function [15]:

$$f_c = a_1 n + a_0 \tag{1}$$

The factors a_1 and a_0 in Eq. (1) are determined using the least square method:

$$a_1 = \frac{\sum_{i=1}^{N}(n_i - n_{mean})(f_{c,i} - f_{cm})}{\sum_{i=1}^{N}(n_i - n_{mean})^2} \tag{2}$$

$$a_0 = f_{cm} - a_1 n_{mean} \tag{3}$$

where N is the number of specimen groups used to establish the f_c-n relationship (N = 20), n_{mean} is the mean rebound number and f_{cm} is the mean concrete strength of all N specimen groups.

The error of the f_c-n relationship is evaluated by the standard deviation S_T expressed as:

$$S_T = \sqrt{\frac{\sum_{i=1}^{N}\left(f_{c,i} - f_{ch,i}\right)^2}{N-1}} \tag{4}$$

in which $f_{c,i}$ and $f_{ch,i}$ are the strengths of the i-th specimen group determined by the compression test and by the f_c - n relationship of Eq. (1), respectively.

In addition to the concrete tests, twelve 16-mm reinforcement specimens from the reinforcing batch of the first building and twelve 20-mm reinforcement specimens from the second building were collected for tensile testing. Before the tensile test, the actual diameter and cross-sectional area of the reinforcement specimens were measured. Fig.5 shows a reinforcement specimen gripped on a WE-1000 hydraulic universal testing machine. The destructive tensile testing process can provide information about the yield strength, tensile strength and ductility of the reinforcement [25].

Fig.5 Tensile test of reinforcement specimen

3.3 On-Site Testing of Columns

For each of the case study buildings, rebound hammer tests were performed on 4 columns to obtain the rebound numbers. In these tests, the rebound hammer was held firmly in a position that allowed the plunger to impact perpendicularly to the surface being tested (Fig.6).

Fig.6 Rebound hammer testing of column

Each column had 6 test areas with impact points positioned about 50 mm apart. For each test area, the rebound numbers were obtained from 16 test points of which 3 maximum readings and 3 minimum readings were removed and the remaining 10 readings were averaged. Therefore, for each case study building we collected 240 usable readings with 24 average rebound numbers from 4 tested columns.

The compressive strength $f_{c,i}$ corresponding to the average rebound number of the i-th test area can be calculated using the relationship of Eq. (1) established previously. Let f_{cm} and S_1 be the mean value and standard deviation of the rebound hammer-based compressive strength for all test areas. Taking account of the error S_T of the f_c-n relationship, the standard deviation S_c and coefficient of variation V_c of the concrete compressive strength are calculated as [15]:

$$S_c = \sqrt{S_1^2 + S_T^2} \tag{5}$$

$$V_c = 0.9\frac{S_c}{f_{cm}} \tag{6}$$

3.4 Design Values of Material Strength

The characteristic compressive strength of concrete f_{ck} is calculated from the mean strength f_{cm} and coefficient of variation V_c with a probability level of being exceeded of 95%:

$$f_{ck} = f_{cm}(1 - 1.64V_c) \tag{7}$$

The characteristic strength of reinforcement f_{yk} is computed from the mean value f_{ym} and coefficient of variation V_s of the yield strength:

$$f_{yk} = f_{ym}(1 - 1.64V_s) \tag{8}$$

The design strengths of concrete f_{cd} and reinforcement f_{yd} are given by Eqs. (9)-(11) where α_c is a factor to convert the cube strength to prismatic strength of the concrete, $\gamma_c = 1.3$ and $\gamma_s = 1.15$ are the partial safety factors for the concrete and reinforcement meant [23].

$$f_{cd} = \frac{\alpha_c f_{ck}}{\gamma_c} \tag{9}$$

$$\alpha_c = 0.77 - 0.001f_{ck} \tag{10}$$

$$f_{yd} = \frac{f_{yk}}{\gamma_s} \tag{11}$$

3.5 Ultimate Strength of RC Column in Combined Bending and Compression

Fig.7 shows the rectangular cross-section of a column subjected to axial compression and bending with typical strain and stress distributions for a position of the neutral axis. Let b, h, A_s, A_{sc}, d, d_{sc}, and c be the section width, section overall depth, area of tensile reinforcement, area of compressive reinforcement, effective depth, depth of A_{sc}, and depth of the neutral axis respectively. The depth a of the equivalent rectangular concrete stress block is taken as $0.8c$ and the ultimate concrete compressive strain ε_{cu} is taken as 0.0035 for normal-strength concrete members.

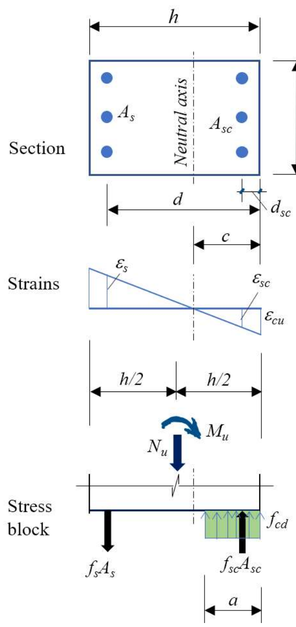

Fig.7 Analysis of column section

The trains ε_s and ε_{sc}, and the stresses f_s and f_{sc}, in the reinforcements A_s and A_{sc} are computed as:

$$\varepsilon_s = \frac{d-c}{c}\varepsilon_{cu} \tag{12}$$

$$\varepsilon_{sc} = \frac{c-d_{sc}}{c}\varepsilon_{cu} \tag{13}$$

$$-f_{yd} \le f_s = \varepsilon_s E_s \le f_{yd} \tag{14}$$

$$-f_{yd} \le f_{sc} = \varepsilon_{sc} E_s \le f_{yd} \tag{15}$$

where E_s is the reinforcement elastic modulus.

From equilibrium conditions, the axial load capacity N_u and moment capacity M_u of the column can be computed as:

$$N_u = f_{cd}ba + f_{sc}A_{sc} - f_sA_s \tag{16}$$

$$M_u = f_{cd}ba\left(\frac{h}{2}-\frac{a}{2}\right) + f_{sc}A_{sc}\left(\frac{h}{2}-d_{sc}\right) + f_sA_s\left(d-\frac{h}{2}\right) \tag{17}$$

Let c change from $2d_{sc}$ to d to find a set of (M_u, N_u) points that constitute part of the interaction diagram of the column as shown in Fig.8. The pure bending strength without axial load M_{uo} can be found by equating N in (16) to zero. The balanced point B in Fig.8 represents a balanced failure with $\varepsilon_s = f_{yd}/E_s$. The interaction diagram also includes a squash load point which represents the ultimate strength in compression without bending N_{uo}:

$$N_{uo} = f_{cd}bh + f_{yd}A_{sc} + f_{yd}A_s \tag{18}$$

We suggest using the area of the safe zone, which is the area bounded by the interaction diagram and the two axes, as a parameter to evaluate the column capacity in combined bending and compression. Dividing the area of the safe zone into segments, the trapezoidal rule for integration can be employed to find the area S of the safe zone:

$$S = \sum\left(N_{u,i+1} - N_{u,i}\right)\frac{M_{u,i+1}+M_{u,i}}{2} \tag{19}$$

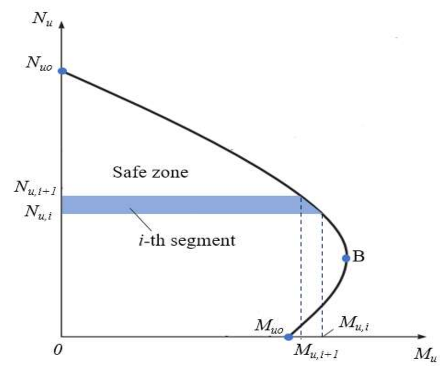

Fig.8 Interaction diagram

4. RESULTS AND DISCUSSIONS

4.1 Correlation between Concrete Strength and Rebound Number

Fig.9 shows the average rebound number n and concrete compressive strength f_c of 20 specimen groups made from the site-mixed B15 concrete of the first building. The measured concrete strength varied from 19.13 to 37.25 MPa with a mean strength f_{cm} of 27.10 MPa. A linear relationship between f_c and n can be developed as:

$$f_c = 2.3213n - 39.1460 \tag{20}$$

where the standard deviation S_T that expressed the error of the f_c-n relationship was 1.91 MPa.

For the ready-mixed B20 concrete of the second building, the average rebound number n and concrete compressive strength f_c acquired from 20 specimen groups are shown in Fig.10. The concrete strength varied from 24.82 to 40.10 MPa with a mean strength f_{cm} of 33.30 MPa. A linear relationship between f_c and n with S_T = 1.72 MPa was found as:

$$f_c = 0.9088n - 1.3793 \tag{21}$$

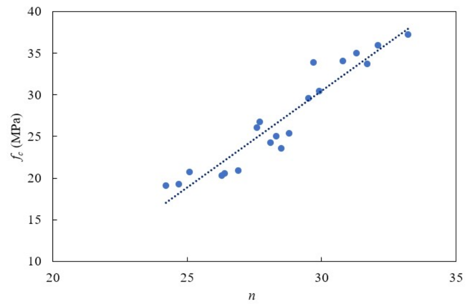

Fig.9 B15 concrete cubes: f_c-n relationship

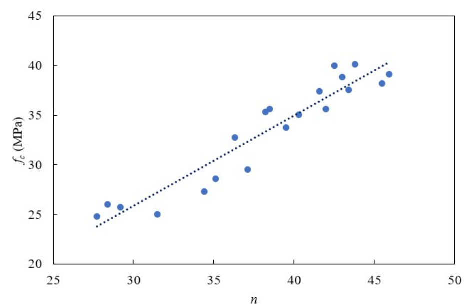

Fig.10 B20 concrete cubes: f_c-n relationship

4.2 Actual versus Codified Strength of Concrete in Existing Columns

According to the Vietnamese concrete design standard [23], the coefficient of variation of concrete strength V_c is taken as 0.135. The B15 concrete (building 1) would have a characteristic compressive strength f_{ck} of 15 MPa, mean strength f_{cm} of 19.27 MPa and design strength f_{cd} of 8.5 MPa. The B20 concrete (building 2) would have f_{ck} = 20 MPa, f_{cm} = 25.69 MPa and f_{cd} = 11.5 MPa.

The hammer test performed on 64 test areas of 4 columns of the first building revealed the rebound readings in the range 24.0 to 30.8, which were translated to compressive strength values of 16.56 to 32.35 MPa via Eq. (20). We had f_{cm} = 25.48 MPa, S_I = 4.54 MPa, S_c = 4.93 MPa and V_c = 0.174. For the columns of the second building, the rebound numbers fluctuated between 27.7 and 48.8, resulting in compressive strength values in the range 23.79 to 42.97 MPa (Eq. (21)) with f_{cm} = 34.21 MPa, S_I = 5.11 MPa, S_c = 5.39 MPa and V_c = 0.142. The characteristic compressive strength f_{ck} and design compressive strength f_{cd} can then be determined using Eqs. (7) and (9).

Tables 1 and 2 compare the concrete strength values predicted by the rebound hammer test (actual values) with those based on the design standard (codified values) for the case study columns. The coefficient of variation of strength of the ready-mixed concrete (building 2) was found to be lower than that of the site-mixed concrete (building 1). Both the site-mixed concrete and ready-mixed concrete had an actual coefficient of variation in compressive strength V_c greater than the standardized coefficient of variation. However, the actual design strength was still greater than the codified design strength because the actual mean strength was 33% greater than the codified mean strength for the concrete grades under consideration.

Table 1 Building 1: concrete strength

Parameter	Actual value	Codified value	Difference
f_{cm} (MPa)	25.48	19.27	33%
V_c	0.174	0.135	29%
f_{ck} (MPa)	18.21	15	21%
f_{cd} (MPa)	10.53	8.5	24%

Table 2 Building 2: concrete strength

Parameter	Actual value	Codified value	Difference
f_{cm} (MPa)	34.21	25.69	33%
V_c	0.142	0.135	5%
f_{ck} (MPa)	26.25	20	31%
f_{cd} (MPa)	15.02	11.5	31%

4.3 Strength and Area of Reinforcement

The codified design strength for 300-MPa reinforcement is 260 MPa. From the reinforcement tensile test we had f_{ym} = 364.6 MPa, V_s = 0.044, f_{yk} = 338.5 MPa and f_{yd} = 294.4 MPa for the reinforcement of the first building. For the second building, we obtained f_{ym} = 382.3 MPa, V_s = 0.052, f_{yk} = 349.5 MPa and f_{yd} = 303.9 MPa. It can be seen that the actual design strength of the 300-MPa reinforcements from two different suppliers used in the two buildings was 13-17% greater than the standardized value.

The actual cross-sectional area of the 16-mm rebar had a mean value of 197.8 mm^2, a coefficient of variation of 0.019, and a characteristic value of 191.6 mm^2 which was 5% less than the nominal area of 201 mm^2. For the second building, the actual cross-sectional area of the 20-mm rebar had a mean value of 308.4 mm^2, a coefficient of variation of 0.018, and a characteristic value of 303.9 mm^2 which was 3% less than the nominal area of 314 mm^2.

4.4 Bearing Capacity of Columns in Combined Bending and Compression

The material properties acquired from the concrete and reinforcement tests were used to build the interaction diagram of the columns. For comparison purposes, the columns' interaction diagrams were also calculated using standardized material properties. The interaction diagrams based on the codified material strengths were entirely enclosed by those based on the actual material strengths, i.e. the actual bearing capacity was greater than the design bearing capacity (Figs.11-12). Using the actual material strengths, the bearing capacity in pure compression N_{uo} increased by 18% for the columns of the first building and 24% for the columns of the second building, as shown in Tables 3 and 4. The bearing capacity in pure bending M_{uo}, primarily dominated by the reinforcement yield strength, was found to increase by 8% for the first building and 12% for the second. Regarding the overall bearing capacity for combined bending and axial compression, the safe zone area S increased by 34% for the columns using site-mixed concrete (building 1) and 47% for the columns using ready-mixed concrete (building 2).

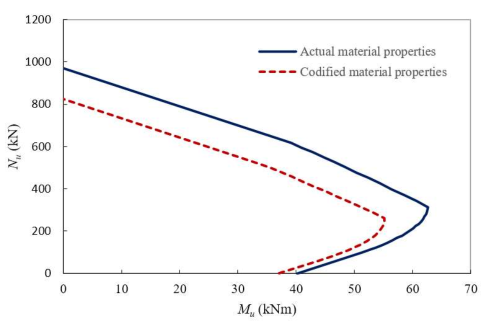

Fig.11 Building 1: interaction diagram of columns

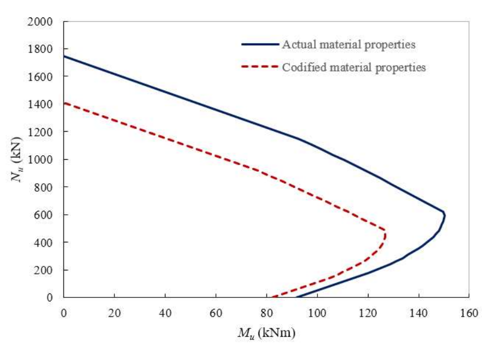

Fig.12 Building 2: interaction diagram of columns

Table 3 Building 1: columns bearing capacity

Parameter	Actual value	Codified value	Difference
N_{uo} (kN)	970.3	823.6	18%
M_{uo} (kNm)	40.2	37.1	8%
S (kN^{2}m)	39571	29463	34%

Table 4 Building 2: columns bearing capacity

Parameter	Actual value	Codified value	Difference
N_{uo} (kN)	1747.7	1409.8	24%
M_{uo} (kNm)	91.9	82.2	12%
S (kN^{2}m)	173302	117593	47%

5. CONCLUSION

In this paper, data obtained from the concrete rebound hammer test and reinforcement tensile test were utilized to estimate the actual bearing capacity of some RC columns in two buildings under construction. From a material strength perspective, the actual compressive strength of the concrete was 24-31% higher than the codified value. From the perspective of structural members' strength, the actual strength was found to be 47% and 34% higher than the standardized strength for the columns using ready-mixed concrete and site-mixed concrete respectively. The bearing capacity of the surveyed columns can hence be considered to completely satisfy the design requirements.

In conclusion, this paper has discussed a fast, cheap, easy-to-use, and non-invasive procedure to validate the strength capacity of existing RC columns in combined compression and bending. However, only the rebound hammer technique was utilized for the estimation of the concrete strength. Future research may consider combining the rebound hammer test with another NDT method such as an ultrasonic pulse velocity test to enhance prediction accuracy.

6. ACKNOWLEDGMENTS

This work was supported by the University of Architecture Ho Chi Minh City (Grant XD-NCKH22).

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