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# In-Place Estimation of Concrete Compressive Strength Using Postinstalled Pullout Test – A Case Study

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**Reference**

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**ABSTRACT**

It was proposed that a 16-story steel framing structure be built on top of an existing 12-year-old 1-story reinforced-concrete structure. The in-place concrete compressive strength of 3 footings and 29 plinths was estimated using a postinstalled pullout test and a core compressive strength test. The influence of different length-to-diameter ratios of the cores and different diameters of cores and the correlation between maximum pullout force and core compressive strength were investigated. The results of the pullout test and core strength test indicate that the concrete compressive strength of footings and plinths was considered structurally adequate as per the acceptance criteria for tested core strength and estimated core strength given by ACI 318, *Building Code Requirements for Structural Concrete and Commentary*, and ACI 228.1R, *In-Place Methods to Estimate Concrete Strength*, respectively. Maximum pullout force had a strong correlation with the core compressive strength. The influence of the different length-to-diameter ratio of cores on the strength correlation was not significant if the raw results of the compressive strength tests were corrected by multiplying the corresponding correction factors for the length-to-diameter ratio given by ASTM C42, *Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete*. The mixed use of the test results of 3.20 and 3.74-in. (81-mm and 95-mm) cores resulted in a decrease in the $R^2$ of the correlation model, compared to that of the correlation model based on 3.74-in. (95-mm) cores. This was attributed to the potentially increased testing error as the diameter of the cores decreased. Recommendations for successfully performing postinstalled pullout tests in the field were proposed. With the use of pullout tests, the project team was able to determine that the existing structural members had sufficient capacity. A delay in the project schedule was avoided.

**Keywords**

in-place concrete strength, postinstalled pullout test, length-to-diameter ratio, core diameter, strength correlation

## Introduction

The estimation of in-place concrete compressive strength is often needed for projects of new construction, structural addition and remodeling, change of use, structural repair, and forensic investigation. Traditionally, concrete cores are retrieved from structures for compressive strength testing [1,2]. This approach may be labor intensive and time consuming if a large number of structural members are under the scope of investigation. In addition, the process of coring may, to some extent, cause damage to the structure. Alternative methods—which reduce the amount of coring, save time and economic cost, and cause no damage or limited superficial local damage to the structure—used to evaluate the in-place concrete compressive strength have been gaining research interest. These methods include, but are not limited to, rebound hammer, ultrasonic pulse velocity, break-off test, penetration resistance, and pullout test, all of which measure the properties of concrete that can be correlated to its compressive strength [1–3]. One of the sources for the most widely followed guidance of performing the in-place concrete strength evaluation is ACI 228.1R, *In-Place Methods to Estimate Concrete Strength*, which was issued by the American Concrete Institute (ACI) Committee 228 [1]. In another publication by the same ACI committee, ACI 228.2R, *Report on Nondestructive Test Methods for Evaluation of Concrete in Structures*, core strength tests and pullout tests are recommended as the primary methods for estimating the in-place concrete compressive strength [4].

The pullout test involves pulling out an insert with an enlarged head embedded in the concrete [1,2,5,6]. The maximum pullout force was measured and correlated with the compressive strength of cylinders or cores. Based on the correlation, in-place concrete strength can be estimated for more structural members if the maximum pullout forces on these members are known. There are two types of pullout tests that use cast-in-place inserts and postinstalled inserts [1,5,6]. The former approach is used for new construction, and a correlation between maximum pullout force and compressive strength of molded specimens (cylinders or cubes) is determined to estimate the in-place concrete strength [2,6]. The later approach was developed for existing structures, and a correlation between maximum pullout force and core compressive strength is determined to estimate the in-place concrete strength [2,6]. Both approaches create a cone-shaped concrete fragment after test completion. Most of the currently available literature is focused on cast-in-place pullout tests, which involve use of a correlation between maximum pullout force and the compressive strength of molded specimens [5–9]. The information necessary for understanding the performance of postinstalled pullout tests is still limited, especially when considering the difference between core and molded specimens from the following aspects:

- The molded specimen often has a better-defined geometry than core specimens. For instance, the side of the core is usually not as straight as that of cylinder.
- The dimensions of different cores retrieved in a project are usually not consistent. For instance, cores with different length-to-diameter ratios may be retrieved because of the restrictions of steel reinforcement layout and dimensions of the structural member. The use of compressive strength test results of cores with various length-to-diameter ratios may affect the reliability of the strength correlation.
- The processes of coring and trimming may cause damage to concrete cores [10].
- Cores are retrieved from structures that, in most cases, have been subjected to years of weathering. The results of a core compressive strength test may have large variance because of possible deleterious chemical reactions, such as alkali-silica reactions, delayed Ettringite formation, and carbonation [2].

These factors may affect the accuracy of the estimated in-place concrete strength using a postinstalled pullout test.

The authors of this article utilized a postinstalled pullout test to evaluate the in-place concrete compressive strength of 32 reinforced concrete members, including plinths and footings. The influence of different length-to-diameter ratios of cores and different diameters of cores on the strength correlation are investigated, which fill some of the knowledge gaps in performing the postinstalled pullout test. Different strength correlation models are comparatively studied. In addition, the cost of pullout tests and core strength tests are discussed.

## Project Information

It was proposed that a 16-story steel framing structure be built on top of an existing 12-year-old 1-story reinforced-concrete structure, which was supported on an isolated footing foundation system. Concrete cracking was observed on some plinths after the soil was excavated at the foundation level. The original structural drawings indicated that the specified 28-day concrete compressive strength of the footings and plinths was 3,000 psi (21 MPa) and 6,000 psi (41 MPa), respectively. However, the concrete mixture design information and concrete material testing records were not available to the project team. In order to assist the project team in determining whether the existing reinforced concrete structure had sufficient capacity to carry the load from the proposed steel structure, a two-phase study on the material properties of the in-place concrete materials was carried out.

In phase one of the study, petrographic examination and a phenolphthalein stain test were performed on concrete cores retrieved from the footings and plinths. The results of petrographic examination indicated some evidence of the occurrence of alkali-silica reaction (ASR) in concrete. However, the ASR gel was mainly confined to the air voids and was not significant enough to cause cracking in the cementitious matrix. Delayed Ettringite formation was not observed. It was also identified by petrographic examination that the footing concrete and plinth concrete both contained crushed limestone coarse aggregate with a maximum size of 1 in. (25 mm) Phenolphthalein stain testing indicated that the maximum depth of carbonation of footing concrete ranged from 1/8 in. (3 mm) to 1/4 in. (6 mm), and the carbonation of plinth concrete was not visually identified.

In phase two of the study, the project team identified 3 footings and 29 plinths as critical structural members, and the in-place concrete compressive strength of these 32 members were to be investigated. The authors of this article performed concrete pullout tests to evaluate the in-place concrete compressive strength following the procedures described in ASTM C900, *Standard Test Method for Pullout Strength of Hardened Concrete* [11]. ACI 228.1R was used as a guide to develop the testing program [1]. ACI 228.1R recommended that a minimum of six locations be selected for performing both core compressive strength tests and pullout tests in order to determine a job-specific correlation between maximum pullout force and core compressive strength [1]. It was also recommended in ACI 228.1R that performing both tests at more than nine locations would probably not be justified economically [1]. The budget that was available for the project also influenced the number of locations that could be selected for performing both tests. In this study, both the concrete core compressive strength test and the pullout test were performed on three footings and twelve plinths to determine the job-specific strength correlation. The in-place concrete compressive strength of the other 17 plinths was estimated based on the strength correlation and measured maximum pullout force from these plinths.

## Test Program

To estimate the in-place concrete compressive strength with core compressive strength test, ASTM C42, *Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete*, recommends the use of core specimens with a diameter that preferably is at least three times the nominal maximum size of the coarse aggregate in the concrete [10]. In the present study, concrete cores with a finished diameter of 3.74 in. (95 mm) (3.74-in. cores) were preferably retrieved. For some of the structural members with the presence of congested steel reinforcement, only cores with a smaller diameter of 3.20 in. (81 mm) (3.20-in. cores) were practical to be retrieved. If 3.74-in. cores were allowed by the steel reinforcement layout, three cores were retrieved from a structural member. If only 3.20-in. cores were allowed, four cores were retrieved because of the consideration of possible greater variance in the compressive strength test results of the smaller-diameter cores. Moreover, concrete cores with a length-to-diameter ratio of 2 were intended to be retrieved. However, because of the presence of congested steel reinforcement in some structural members, is was only feasible to retrieve concrete cores with smaller length-to-diameter ratios. In the present study, the length-to-diameter ratio of cores obtained varied from 1.22 to 1.97. In order to limit the effect of length-to-diameter ratio on the core compressive strength test, the raw compressive strength test results for cores with a length-to-diameter ratio less than 1.75 were corrected by multiplying the corresponding correction factors for length-to-diameter ratio, as illustrated in Section 7.9 of ASTM C42 [10]. This is a common practice in the industry.

To estimate the in-place concrete compressive strength with pullout test, three pullout tests were initially performed at locations close to where the concrete cores were retrieved on each structural member. The influence of carbonation of concrete on the pullout test was ignored, as carbonation of concrete was identified to be insignificant by phenolphthalein stain test. The pullout tests were performed by four well-trained technicians. If abnormal measurements of maximum pullout force were identified, additional tests were performed in order to ensure that three reliable maximum pullout force measurements were available for result-analyzing purposes. In the present study, the observed possible causes of abnormal measurements included cracks, metal wire, or voids present on the conic surface of the concrete fragment.

## Test Methods

### GROUND-PENETRATING RADAR

A ground-penetrating radar (GPR) with a model name of PS 1000 (Hilti Group, Schaan, Liechtenstein) was used to locate the steel reinforcement in the structural members. The coring and pullout strength test locations were selected in such a way that the steel reinforcement would not be damaged by coring and that the steel reinforcement is outside the expected conical failure surface by more than the greater of one bar diameter and maximum size of aggregate.

### CONCRETE CORE COMPRESSIVE STRENGTH

Cores were retrieved from the sides of plinths in a horizontal direction, and from the tops of footings in a vertical direction. Concrete cores were retrieved, transported, conditioned, and tested following the procedures described in ASTM C42 [10].

### POSTINSTALLED PULLOUT TEST

A commercially branded test system was used to prepare the concrete test specimen, applying loading and obtaining the maximum pullout force measurements. The pullout test was performed following the procedures described in ASTM C900 [11]. The schematic of a prepared concrete specimen ready for loading is shown in Fig. 1.

A typical view of a completed pullout test is shown in Fig. 2.

FIG. 1

Postinstalled pullout test configuration.

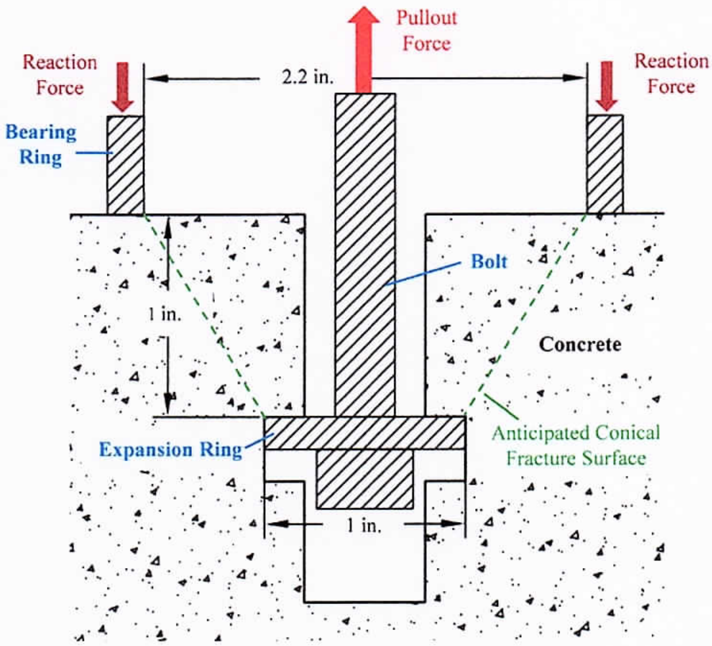
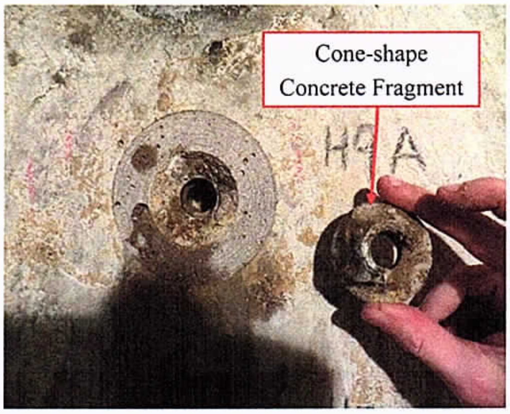


FIG. 2

Cone-shaped concrete fragment after completion of pullout test.




## Results and Discussions

### MAXIMUM PULLOUT FORCE AND CORE COMPRESSIVE STRENGTH

The results of the pullout test and core compressive strength test performed on the twelve plinths and three footings are shown in Table 1. It should be noted that the core compressive strength values presented in Table 1 are raw test results corrected by multiplying the corresponding correction factors for the length-to-diameter ratios given by ASTM C42 [10].

The results of core compressive strength tests did not identify any individual core with compressive strength lower than 75 % of the corresponding specified 28-day concrete

TABLE 1

Results of pullout test and core compressive strength test.

| | Maximum Pullout Force | | Compressive Strength of Cores (after Correction)[b] | | | |
|---|---|---|---|---|---|---|
| Member Name | Average (kip) | COV[a] (%) | Average (psi) | COV[a] (%) | Diameter of Cores (in.) | Length-to-Diameter Ratio of Cores (Sulfur Capped) |
| Plinth 1 | 10.2 | 5 | 9,237 | 5 | 3.74 | 1.74–1.90 |
| Plinth 2 | 9.3 | 8 | 6,495 | 3 | 3.74 | 1.31–1.93 |
| Plinth 3 | 11.3 | 6 | 9,265 | 4 | 3.74 | 1.87–1.95 |
| Plinth 4 | 9.4 | 2 | 7,340 | 5 | 3.20 | 1.53–1.63 |
| Plinth 5 | 8.3 | 6 | 7,210 | 3 | 3.20 | 1.22–1.72 |
| Plinth 6 | 11.6 | 7 | 9,207 | 5 | 3.74 | 1.90–1.95 |
| Plinth 7 | 10.0 | 12 | 7,633 | 2 | 3.20 | 1.84–1.97 |
| Plinth 8 | 10.1 | 1 | 8,705 | 3 | 3.74 | 1.23–1.71 |
| Plinth 9 | 11.4 | 9 | 8,250 | 0 | 3.74 | 1.50–1.95 |
| Plinth 10 | 10.8 | 9 | 9,040 | 0 | 3.74 | 1.55–1.93 |
| Plinth 11 | 7.4 | 5 | 6,093 | 5 | 3.74 | 1.47–1.79 |
| Plinth 12 | 10.1 | 7 | 5,830 | 6 | 3.20 | 1.53–1.84 |
| Footing 1 | 5.5 | 6 | 3,655 | 1 | 3.74 | 1.90–1.93 |
| Footing 2 | 4.8 | 3 | 3,487 | 6 | 3.74 | 1.90–1.93 |
| Footing 3 | 3.2 | 10 | 3,250 | 1 | 3.74 | 1.79–1.95 |

*Note:* 1 kip = 4.448 kN; 1 psi = 0.0069 MPa; 1 in. = 0.0254 m; [a] Coefficient of Variation; [b] Compressive strength of cores are raw test results corrected by multiplying the corresponding correction factors for length-to-diameter ratio.

compressive strength or any average core compressive strength of a structural member lower than 85 % of the corresponding specified 28-day concrete compressive strength. This indicated that the concrete compressive strength of footing and plinth represented by the cores was considered structurally adequate as per the acceptance criteria for the core strength test given by ACI 318, *Building Code Requirements for Structural Concrete and Commentary* [12].

It is shown in Table 1 that the length-to-diameter ratios of cores were different. To determine the correlation between the maximum pullout force and the core compressive strength, it was assumed that the influence of length-to-diameter ratio on the core compressive strength could be limited by correcting the raw results of the compressive strength test by multiplying the corresponding correction factors for the length-to-diameter ratio given by ASTM C42 [10].

### CORRELATION BETWEEN MAXIMUM PULLOUT FORCE AND COMPRESSIVE STRENGTH OF 3.74-IN.-DIAMETER CORES

The maximum pullout force measurements and 3.74-in. core compressive strength measurements obtained from the eleven structural members, including three footings and eight plinths, were used to develop a correlation between maximum pullout force and 3.74-in. core compressive strength. The average maximum pullout force was plotted against the average core compressive strength for each of the eleven structural members. A power function and a natural exponential function were used in the regression analyses for comparison purpose. The correlation models are shown in Eqs 1 and 2.

$$y = 905.13\,x^{0.9413}, \quad R^2 = 0.9137 \tag{1}$$

$$y = 1941.7\,e^{0.1385\,x}, \quad R^2 = 0.9411 \tag{2}$$

In both Eqs 1 and 2, $x$ is the average maximum pullout force (unit: kip), and $y$ is the average compressive strength (unit: psi) of cores with a diameter of 3.74 in. (95 mm).

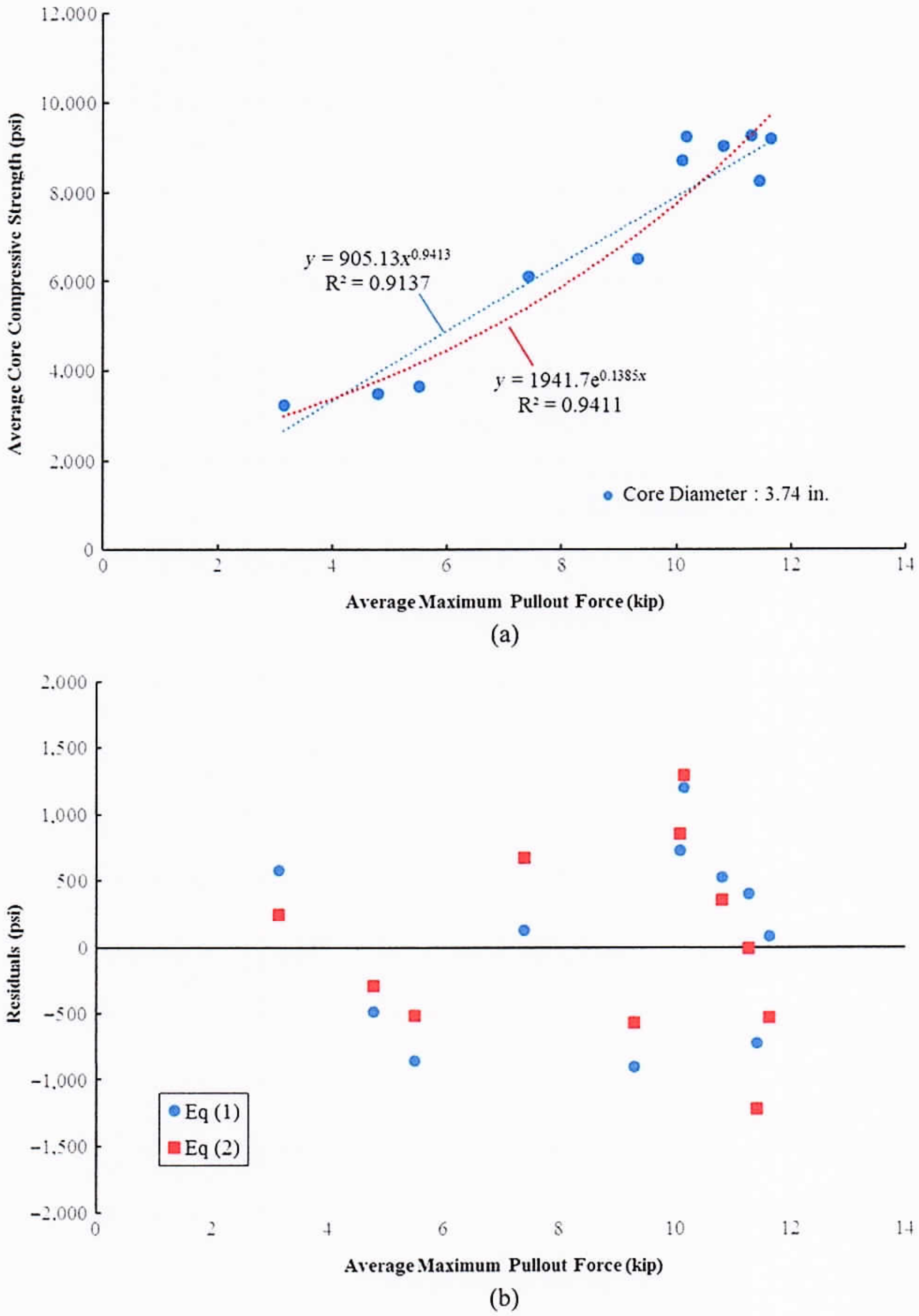
It is noted that power function, Eq 1, is not the best fit model from a standpoint of $R^2$. A higher $R^2$ can be achieved by using a natural exponential function. However, a natural exponential function does not seem to have a physical meaning in the case where the maximum pullout force equals zero and the core compressive strength is estimated to be 1,941.7 psi (13.4 MPa). In the present study, Eq 1 is used to estimate the in-place concrete compressive strength.

The correlation models and the residual plots are shown in Fig. 3a and b, respectively.

As shown in Fig. 3a, maximum pullout force is strongly correlated to the core compressive strength, as reviewed by the high $R^2$ values of both Eqs 1 and 2. The residuals generally dispersed around the zero axis.

It should be noted that both Eqs 1 and 2 were based on the assumption that the influence of length-to-diameter ratio on the core compressive strength could be limited by correcting the raw results of the compressive strength test by multiplying the corresponding correction factors for the length-to-diameter ratio given by ASTM C42 [10]. Considering the high value of $R^2$ in the correlation equations, this assumption appears to be valid in this study.

**FIG. 3** Correlation between average maximum pullout force and average compressive strength of (a) 3.74-in. cores and (b) residual plots.




## INFLUENCE OF CORE DIAMETER ON STRENGTH CORRELATION

A problem may come up when the coring crew find out that concrete cores with the initially intended diameter cannot be retrieved practically because of the congested reinforcement in some of the structural members or because cores with the initially intended diameter have already been retrieved from other structural members. The question of concern is whether cores with different diameters can be used together to develop a correlation or not. In one of the publications by National Ready Mixed Concrete Association, it is stated that the volume effect on the compressive strength of cores with diameters between 2 (51 mm), 3 (76 mm), and 4 in. (102 mm) is not significant, and cores with a diameter as low as 1.6 times the maximum nominal aggregate size can yield the same mean compressive strength of cores with a larger diameter [13]. This literature also recognized that the testing error increased as the diameter of the cores decreased [13].

In the present study, the results of the compressive strength test of cores with diameters of 3.20 and 3.74 in. (81 mm and 95 mm) were used together to determine a strength correlation, in comparison to the correlation determined based on maximum pullout force and compressive strength of 3.74-in. cores alone. A power function was used for the regression analysis. The correlation model is shown in Eq 3.

$$y = 952.18\,x^{0.9086}, \quad R^2 = 0.865 \tag{3}$$

where $x$ is the average maximum pullout force, and $y$ is the average compressive strength of cores with diameters of 3.20 (81 mm) and 3.74 in. (95 mm). It is noted that the $R^2$ of Eq 3, which is 0.865, is smaller than that of Eq 1.

The correlation model and the residual plot are shown in Fig. 4a and b, respectively.

As shown in Fig. 4a, the correlation between average maximum pullout force and average compressive strength of cores with diameters of 3.20 (81 mm) and 3.74 in. (95 mm) is still strongly indicated by an $R^2$ of 0.865. The incorporation of test results of 3.20-in. cores in the correlation model results in a decrease in the value of $R^2$. This can be attributed to the possible increase in the testing error as the diameter of the cores decreases. A correlation model with a lower $R^2$ may cause an increase in the uncertainty of the estimated core compressive strength. Thus, the strength correlation should be developed based on test results from cores that have the same diameter. If the test results of cores that have different diameters must be used together in order to develop a strength correlation, it should be kept in mind that the potential of a higher uncertainty of the estimated core compressive strength may increase [13].

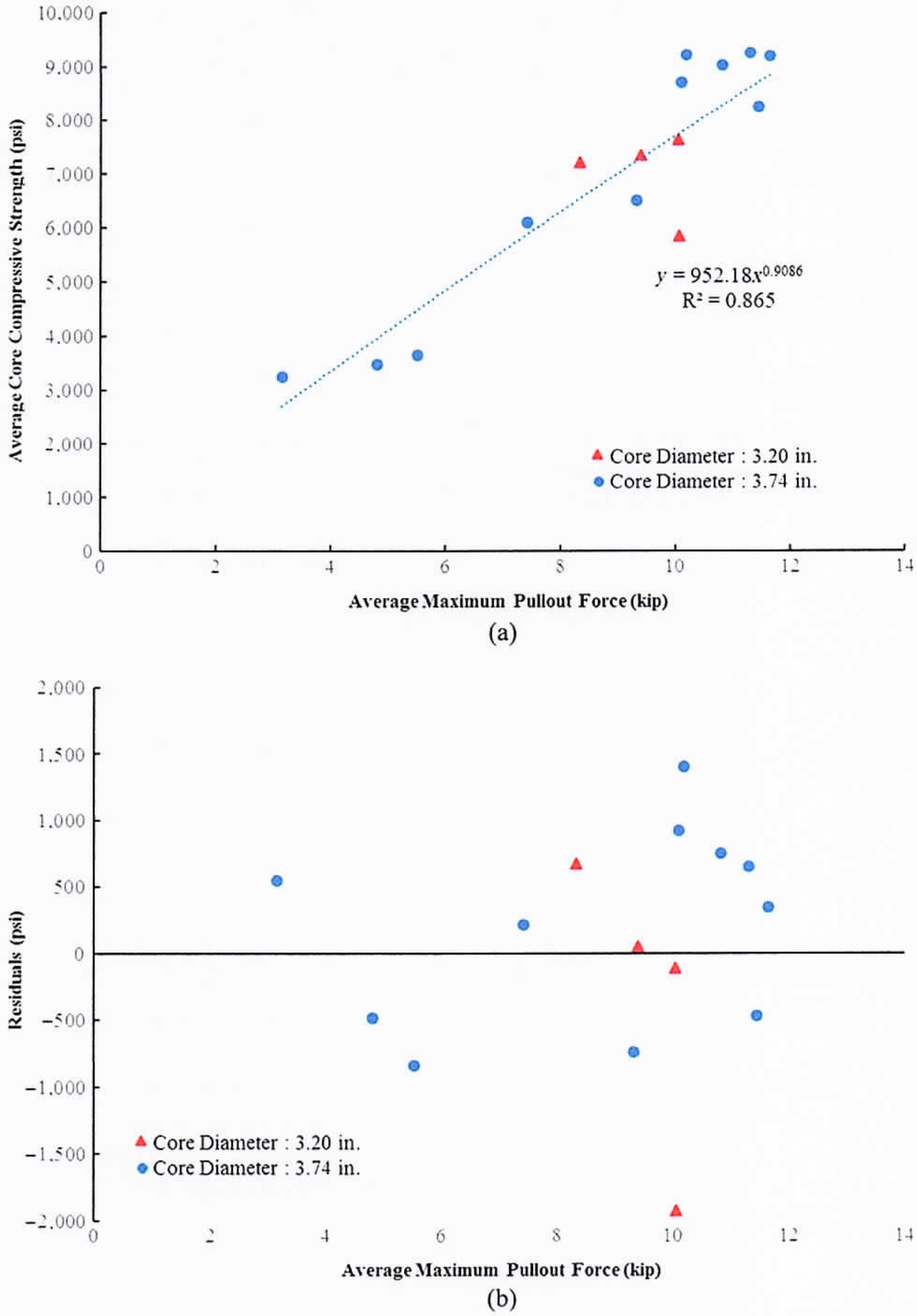
## COMPARISON OF STRENGTH CORRELATION MODELS

Based on a review of the currently available literature, studies on the correlation between maximum pullout force measured from a postinstalled pullout test and core compressive strength are limited. Two correlation models presented in the currently available literature are studied in comparison with Eq 1. One correlation model was developed based on a study of postinstalled pullout tests on bridges, which was performed by Moczko, Carino, and Petersen, and another model was developed based on 18 different studies and claimed to be a general model for estimating the strength of concrete cylinders [2,6]. The testing equipment used in the study by Moczko, Carino, and Petersen was similar to what was used in the present study. The three correlation models are summarized in Table 2.

The comparison of three correlation models are performed based on the results of a 3.20 and 3.74-in. (81-mm and 95-mm) core strength test and corresponding pullout test. The comparison is shown in Fig. 5.

It should be noted that the comparison study is performed based on the test results of 3.74-in. cores, which have a compressive strength ranging from 3,250 to 9,265 psi

**FIG. 4** Correlation between average maximum pullout force and average compressive strength of (a) 3.20 and 3.74-in. cores and (b) residual plot.




(22 MPa to 64 MPa). As it is shown in Fig. 5, at a given maximum pullout force, the Moczko model results in a slightly lower estimation of in-place concrete compressive strength than Eq 1 when the concrete compressive strength is lower than about 5,000 psi

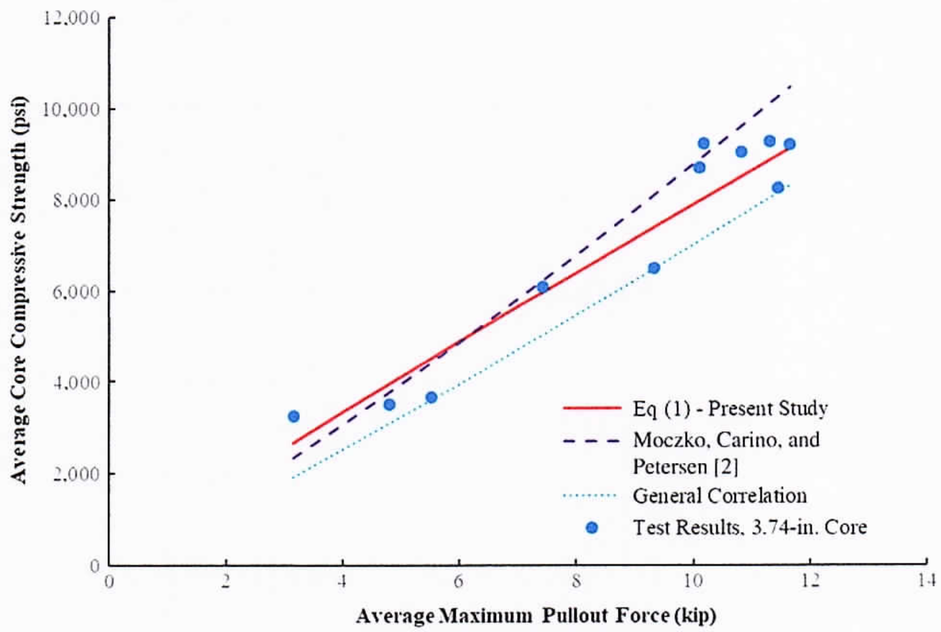
TABLE 2

Strength correlation models for the estimation of in-place concrete compressive strength.

| Correlation Model Name | Model Expression | Test Method |
|---|---|---|
| Eq 1, present study | $y = 905.13\ x^{0.9413}$ where $x$ is the maximum pullout force (unit: kip), and $y$ is the concrete compressive strength (unit: psi) | Core diameter: 3.74 in. (95 mm); Length-to-diameter ratio: 1.23–1.95 Pullout test equipment: CAPO[a]; Conical concrete fragment geometry: see Fig. 1 |
| Moczko, Carino, and Petersen [2] | $f_{core} = 0.77\ F^{1.15}$ where $F$ is the maximum pullout force (unit: kN), and $f_{core}$ is the concrete compressive strength (unit: MPa) | Core diameter: 4.0 in. (102 mm) Length-to-diameter ratio: 1.0 Pullout test equipment: CAPO; Conical concrete fragment geometry: see Fig. 1 |
| General correlation [6] | $f_{cylinder} = 0.69\ F^{1.12}$ where $F$ is the maximum pullout force (unit: kN), and $f_{cylinder}$ is the concrete compressive strength (unit: MPa) | Based on various studies using cast-in-place pullout test and post installed pullout test. |

*Note:* [a] CAPO = postinstalled pullout test equipment developed by Germann Instruments, Inc.

FIG. 5 Comparison of strength correlation models.




(34 MPa), and a higher estimation of in-place concrete compressive strength than Eq 1 when the concrete compressive strength is higher than about 5,000 psi (34 MPa). The general correlation results in a lower estimation of in-place concrete compressive strength than Eq 1. The Moczko model appears to overestimate the concrete compressive strength as the concrete compressive strength increases close to 9,265 psi (64 MPa), and the general correlation generally underestimates the concrete compressive strength. Based on the materials and test methods used in the present study, it seems to be conservative to use the general correlation to estimate the in-place concrete strength in the case that a job-specific correlation is not available.

## ESTIMATION OF IN-PLACE CONCRETE COMPRESSIVE STRENGTH

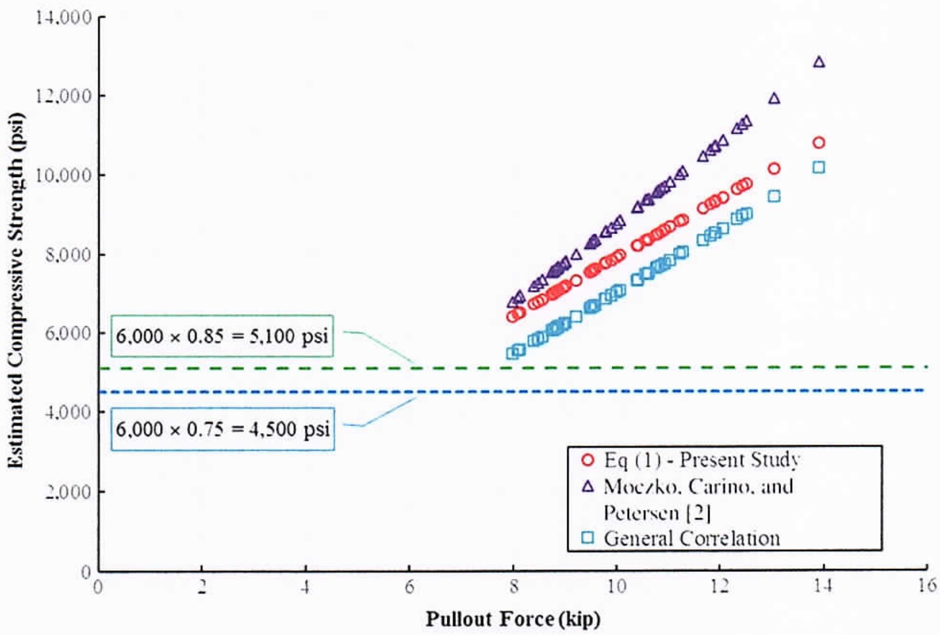
The estimation of in-place concrete compressive strength based on a maximum pullout test is essentially estimating the compressive strength of concrete cores that have not actually been taken from the structural members. The estimation of in-place concrete compressive strength requires a job-specific correlation between maximum pullout force and core compressive strength, as recommended in ACI 228.1R [1]. In the present study, Eq 1 is the job-specific correlation that is used to estimate the in-place concrete compressive strength of 17 plinths, which had not been cored. The estimation results based on Eq 1 are shown in Fig. 6. The estimation results based on the Moczko model and the general correlation are also shown in Fig. 6 for reference. Two threshold values per ACI 228.1R, which are 85 % of the specified 28-day concrete compressive strength and 75 % of the specified 28-day concrete compressive strength, are presented in Fig. 6.

The results of the estimated in-place concrete compressive strength by Eq 1 did not identify any individual value lower than 75 % of the specified 28-day concrete compressive strength or any average in-place concrete compressive strength of a structural member lower than 85 % of the specified 28-day concrete compressive strength. This indicated that the concrete compressive strength of the 17 plinths estimated from the pullout test was considered structurally adequate as per the acceptance criteria given by ACI 221.1R, *Report on Alkali-Aggregate Reactivity* (Reapproved 2008) [1].

## DISCUSSION OF THE COST OF PULLOUT TEST AND CORE STRENGTH TEST

As recommended in ACI 228.1R, in order to determine the correlation between maximum pullout force and core compressive strength, at least six locations should be selected for retrieving at least twelve cores (two cores at each location) for determining the core

FIG. 6 Estimation of in-place concrete compressive strength of plinths.



compressive strength [1]. The concrete strength at these six locations should cover the widest range of concrete compressive strength that is under investigation. The use of the pullout test does not eliminate the need to retrieve cores for the compressive strength test, but it does reduce the need for coring in evaluation of the concrete strength of a large number of structural members [1,11]. From the standpoint of saving a project's schedule and cost, pullout tests are not preferred over core compressive tests when the concrete compressive strength of no more than six locations is to be evaluated.

Based on the authors' field experience in the present project, it takes 30 to 40 minutes for a well-trained technician to complete one pullout test, which includes GPR scanning, grinding the concrete surface, drilling, undercutting the slot, expanding the insert, loading, and patching the concrete surface. For the core compressive strength test, it takes about 15 minutes for a crew of two technicians to retrieve one core, including time for GPR scanning, coring, and patching, and about 15 minutes for a technician in the laboratory to complete a compressive strength test, which includes trimming, capping, and loading. From the standpoint of saving man-hours, pullout testing may not show significant advantages over core compressive strength testing. It should be noted that the actual man-hours used for both pullout tests and core strength tests may be increased because of any uneven surface, congested steel reinforcement, hard aggregate, and high concrete strength of the structural member. However, the concrete strength can be estimated from maximum pullout force right after the completion of a test instead of waiting for 6 to 7 days to obtain a test result from the core compressive strength test. Moreover, if an abnormal measurement is identified, a technician is able to perform additional pullout tests immediately onsite.

In the present project, with the use of the pullout test, the project team was able to determine that the existing structural members had sufficient capacity, and injection of high-modulus epoxy was proposed to repair the concrete cracks. A significant delay in the project schedule was avoided.

## Conclusions

In this study, the in-place concrete compressive strength of 3 footings and 29 plinths was investigated using a postinstalled pullout test. The results presented in this study contributed to the existing knowledge of the pullout test. Based on the materials and test methods used in this study, the following conclusions can be drawn:

(1) The results of the core compressive strength test and pullout test indicated that the concrete compressive strength of footings and plinths was considered structurally adequate as per the acceptance criteria for tested core strength and estimated core strength given by ACI 318 and ACI 228.1R, respectively.
(2) Maximum pullout force had a strong correlation with the core compressive strength.
(3) The influence of the different length-to-diameter ratio of cores on the strength correlation was not significant if the raw results of the compressive strength test were corrected by multiplying the corresponding correction factors for length-to-diameter ratio given by ASTM C42.
(4) The mixed use of test results of 3.20 and 3.74-in. cores resulted in a decrease in the $R^2$ of the correlation model, compared to that of the correlation model based on 3.74-in. cores. This can be attributed to the potentially increased error of compressive strength test as the diameter of the cores decreased.

(5) A job-specific strength correlation should be used for the estimation of in-place concrete strength. In the case where a job-specific correlation is not available, it is conservative to use the general correlation for the estimation of in-place concrete strength.

## Recommendations

Successful implementation of a pullout test relies on every stage of the project, including pretask planning, pullout test specimen preparation, testing, and test results analysis. Based on the authors' experience, the following is recommended:

(1) GPR scan of structural members is recommended during pretask planning. This is to determine the largest allowable diameter of cores to be retrieved and the locations of coring. Moreover, the locations of pullout testing and coring can be arranged in such a way that pullout tests can be performed on structural members that have relatively congested steel reinforcement where coring is difficult.
(2) Petrographic examination of concrete is recommended as part of pretask planning to identify the type of aggregate and size of aggregate if the historic information is not available. The petrographic examination can also review if ASR, delayed Ettringite formation, and carbonation exists in concrete, although their influence on the results of pullout testing is still unclear based on currently available literature.
(3) The use of a metal detector is recommended during the preparation of pullout test specimens, as some of the small metal wire may not be detected by GPR.
(4) After the completion of specimen preparation, the dimensions of the specimen, such as depth of drilled holes and diameter of undercut slots, should be checked.
(5) The appearance and dimensions of the conic concrete fragment formed after the completion of the pullout test should be checked and documented. The presence of cracks, metal wire, or voids on the conic surface of the concrete fragment may cause abnormal maximum pullout force measurement.
(6) The correlation between maximum pullout force and core compressive strength should be determined from cores that have the same diameter.

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