EFFECT OF MISALIGNMENT ON PULL-OFF TEST RESULTS:
NUMERICAL AND EXPERIMENTAL ASSESSMENTS

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K. von Fay, G. Moczulski and M. Morency

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Materials science) from Laval University.
ABSTRACT

The successful application of a concrete repair system is often evaluated through pull-off testing. For such in-situ quality control (QC) testing, the inherent risk of misalignment might affect the recorded value and eventually make a difference in the acceptance of the work. So far, the issue of eccentricity in pull-off testing has been ignored in field practice, because it is seen as an academic issue. This paper presents the results of a project intended to quantify the effect of misalignment on pull-off tensile strength evaluation and provide a basis for improving QC specifications if necessary. The test program consisted first in an analytical evaluation of the problem through 2-D FEM simulations and, in a second phase, in laboratory experiments in which the test variables were the misalignment angle (0°, 2° and 4°) and the coring depth (15 mm [1.18 in.], 30 mm [2.36 in.]). It was found that calculations provide a conservative but realistic lower bound limit for evaluation the influence of misalignment upon pull-off test results: a 2° misalignment can be expect to yield a pull-off strength reduction of 7 to 9 % respectively for 15-mm [1.18-in.] and 30-mm [2.36-in.] coring depths, and the corresponding decrease resulting from a 4° misalignment reach between 13 and 16%; From a practical standpoint, the results generated in this study indicate that when specifying a pull-off strength limit in the field, the value should be increased (probable order of magnitude: 15%) to take into account the potential reduction due to testing misalignment.

Keywords: bond, coring, inclination, misalignment, numerical simulations, pull-off test, repair, stress concentration.
INTRODUCTION

Repairing and overlaying of deteriorated concrete structures are intended to extend their useful service life, to restore their load-carrying capacity and stiffness, and/or sometimes to increase their load-bearing capacity. In order to achieve satisfactorily any of these objectives, full composite action of the repaired structure is a prerequisite, which implies the development of a sufficiently strong and lasting bond between the existing substrate and the newly cast material.

Concrete repair process usually involves the removal of deteriorated or contaminated material and surface preparation prior to application of a repair material. The residual surface characteristics can significantly affect the bond strength and long-term performance of a repair system. Although it is not a common practice yet, mechanical integrity of the prepared concrete substrate should be assessed prior to repair as part of the QC operations.

The pull-off test is a simple and effective test for evaluating both the mechanical integrity of the substrate prior to repair and the interface bond strength in the composite repaired structure. As any other direct tensile loading experiment for concrete, the results yielded with test procedure are sensitive to different parameters. In fact, it is even more sensitive because it is carried out in field conditions. In a previous research effort by some of the authors, the influence of different test parameters upon the recorded strength was investigated, namely the dolly size (thickness, diameter), the core drilling depth, the loading rate, and the number of tests. Diameter of the dolly and core depth were found the most significant parameters affecting the measured tensile strength. Geometry of the dolly and core drilling depth into the substrate were also found to be critical factors when testing for bond in repair.
Another potentially influential parameter of the pull-off test, namely the test alignment, has not received much attention yet. Still, the primary requirement in any direct tension test method is to ensure the pulling force is aligned with and parallel to the specimen axis at all times in order to avoid bending effects. Two main causes may usually induce misalignment in a pull-off experiment: inclination of the core axis caused by inaccurate core drilling (Fig.1a)) and inclination of the pulling force caused by inaccurate positioning of the dolly (Fig. 1b)). Real world, on-site conditions are often limiting the capability of the personnel performing the test to avoid the misalignment situations. Pull-off test misalignment very often arises from difficult on-site conditions, such as a highly irregular support preventing a proper installation of the drilling system and thus leading to inaccurate coring. Special devices can help limiting the risk for loading misalignment. For instance with the Limpet device, the load is applied through a guiding rod.

Austin et al. investigated the effect of misalignment on recorded pull-off strength data. The average eccentricity in their experiments was 1.5 mm [0.059 in.] at a depth of 50 mm [1.97 in.], translating into an angle of inclination of 1.7°. The study concluded that such a misalignment caused an increase in maximum stress of the order of 20% at the core periphery. Cleland and Long performed numerous tests on cores drilled to a depth up to 40 mm into the repair substrate and inclination to the vertical of up to 20° in order to evaluate what effect it has on the measured pull-off bond strength. The authors proposed a correction factor to be applied to the measured results based on the magnitude of the inclination angle:
\[
F_{lt} = \frac{1}{[1 - (\frac{8 \cdot \tan \alpha}{D}) \cdot y]}
\]

where \( \alpha, D, y \) are the angle of inclination of the coring axis (with respect to an axis normal to the surface), the core diameter, and the coring depth respectively, as shown in Fig. 2.

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Misalignment in pull-off tests may have a substantial influence upon test result for angles of inclination of more than 5° (Fig. 2). Reduction in core depth or increase in dolly diameter tends to minimize the negative effects of misalignment. It should be stated, however, that the above conclusions are strictly theoretical in nature, as they do not take into account such factors as potential stress relaxation and the possibility that the core brittle zones are not necessarily corresponding to the stress concentration zones.

These are only geometrical and theoretical considerations. The research work reported in this paper was intended to verify these conclusions by means of numerical simulations and experimental assessment.

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RESEARCH SIGNIFICANCE

Practical experience with in-situ pull-off testing shows that it is next to impossible to drill cores exactly at 90° to the surface and install dollies with the adhesive perfectly parallel to the tested concrete surface, even with the greatest care. Moreover, a misalignment angle up to 5 cannot be easily detected by human eye. In order to evaluate the pull-off test result sensitivity to theses parameters, an experimental program aiming at answering the following questions was undertaken:

• What is the influence of minor load misalignments, i.e. within naked-eye detection
capability, upon pull-off strength test results?

- Do coring and pulling load misalignments influence the results differently?

The results are anticipated to provide guidance towards improved reliability of pull-off strength test results and adapted means, if required, to ensure that the test results are valid.

**METHODOLOGICAL APPROACH**

The objective of this program was to evaluate the effect of coring and/or load misalignment upon the results yielded in pull-off tests, either for the assessment of (a) quality/integrity of a concrete substrate (monolithic), or (b) bond strength in a repair system (composite). A theoretical analysis based on finite-element numerical calculations was first carried out to determine whether the core axis and load misalignment could influence the pull-off test results in a different fashion and assess the overall sensitivity of the results to the experimental bias. A test program was then conducted in the laboratory, involving experiments on both monolithically concrete substrates and composite repair systems.

The following parameters were addressed in the numerical analysis and laboratory experiments:

- Coring axis inclination angle;
- Pulling force inclination angle;
- Core depth in the substrate.

The numerical and experimental test programs are summarized in Table 1. In each case, the test parameter values were selected to cover the range of possibilities encountered in practice:
coring / pulling misalignment is investigated up to an angle that can be detected by the naked eye, whereas coring depth values are representative of most common standard procedures for pull-off testing.

Numerical calculations

Finite element (FEM) calculations were performed using the Lagaprogs software\textsuperscript{21} (tool developed at the University of Liège, Belgium) to predict the stress development within and around the cored area in a concrete substrate, assuming a perfectly elastic behavior, isotropic concrete properties, and isothermal conditions\textsuperscript{22}. With these assumptions, it was not possible to evaluate the theoretical ultimate load and the maximum load considered in the analysis was limited to 50\% of the ultimate load (corresponding to a testing stress of 0.50 MPa [72.5 psi]).

The pull-off testing experiment was addressed as a two-dimensional plane strain problem. The typical boundary conditions and loading scheme considered in the simulations are presented in Fig. 3. The load was assumed to be distributed uniformly over the specimen top surface, implying that the results are not influenced by the dolly material characteristics and geometry. Fig. 4 shows an example of the mesh used for the FEM-based simulations (example shown: angle of inclination of 4° and a core depth of 30 mm [2.36 in.]). The 2-D analysis was performed over the longitudinal cross section. As shown in Figs. 4 and 7, three different mesh sizes were used depending on the area: 1) within the core and below; 2) in the slab outside the core; 3) immediately below the saw cut. The mesh implemented within and right below the cored area was denser than in the surrounding slab bulk concrete, in order to study more finely the local stress distribution in the critical areas, especially in the vicinity of the cut. An even finer squared mesh was used immediately below the saw cut (under points A
and B in Fig. 4), the size of the element corresponding to the thickness of the saw.

The concrete physical characteristics assumed in the analysis were the following:

- Elasticity modulus: 30 GPa [4350 lb/in²];
- Poisson ratio: 0.20;
- Density: 2500 kg/m³ [4215 lb/yd³];
- Test load to yield an average stress of 1 MPa [145 psi]: 7.85 kN [1,77 lb].

Analysis of the stress distribution in the critical areas of the cored substrate is expected to help evaluating the sensitivity of test results to misalignment and to determine whether load inclination and coring axis shift exert similar influence.

**Laboratory experiments**

The experimental test program was subdivided into two parts. In Part I, tests were performed on monolithic test slabs to assess the influence of misalignment on tensile pull-off strength data and to compare the results with modeling. In Part II, tests series were conducted on repaired slabs.

**Part I – Experiments on monolithic test slabs**

Series of six 600×400×100 mm [23.62×15.75×3.94 mm] concrete test slabs were prepared for Part I using three different ordinary Portland cement concrete mixtures, C30/37, C40/50, and C50/60, named after their respective design strength ranges in MPa units. The concrete mixture composition details are summarized in Table 2. During the initial 48-hour period after casting, the slabs were covered with polyethylene (wet burlap inserted after 24 hours).
At 48 hours, they were demolded and stored in lime-saturated water up to 28 days. Five pull-off tests have been carried out for each concrete composition.

The three mixtures were characterized for compressive strength at 28 days. The results are summarized in Table 3.

After 28 days of moist curing, the concrete slab surfaces were prepared by sandblasting for pull-off testing. The surface roughness was then evaluated with the sand-patch test method (EN 13036/EN 1766/ASTM E 965). The texture depth values recorded for the three different concrete mixtures were comparable, the overall average being equal to 0.90 mm [0.035 in.].

As in the numerical analysis, the tensile pull-off tests were conducted on test specimens prepared with different core depths and inclinations. Core depths of 15 mm [1.18 in.] and 30 mm [2.36 in.] and coring axis inclination angles of 0°, 2° and 4° were again investigated. The different core inclinations were achieved using the special device shown in Fig. 6 a), which allows controlling the inclination of the core drill axis (Fig. 6 b)) with a precision of 0.1°. Taking into account the maximum aggregate size of the concrete mixtures (20 mm), 80-mm diameter cores were drilled for pull-off testing (80 mm diameter and 30 mm [2.36 in.] thick steel dollies). Steel dollies were carefully installed using epoxy resin (Fig. 6 c)) and the pull-off test device was then positioned on the concrete substrate (Fig. 6 d)). Prior to testing, the adhesive was allowed to cure for 24 hours. Once the testing rig was installed and connected to the dolly, the pulling load was increased at a constant rate of 0.05 MPa/s [7.25 psi/s] until failure.
In order to better appraise the results in view of pull-off test variability, series of complementary direct tensile strength test were performed on cores extracted from the test slabs.

After each pull-off test, the fracture surfaces were carefully examined. Exposed aggregate area has been selected as criteria for analysis in trying to evidence a possible correlation between low experimental pull-off strength values and the lack of adhesion between the paste and aggregates.

THEORETICAL ANALYSIS

Source of misalignment

First, a sensitivity analysis was performed in order to establish whether the two possible sources of misalignment, i.e. coring misalignment and pulling misalignment, exert the same influence on pull-off test results. Numerical simulations were carried out assuming only core inclination load inclination angles of 4° and a core depth of 30 mm [2.36 in.]. Results are summarized in Table 4.

For a given shift angle, both types of misalignment yield very similar results and it can be concluded that their influence upon pull-off test results is comparable. A slight difference is found when comparing transverse stresses (σₓ), but it is sufficiently small to assume that it does not affect the pull-off strength data within its intrinsic range of variability.

Influence of core depth and misalignment angle

Initially axi-symmetrical with respect to the vertical axis under a perfectly vertical load, the
stress field induced by the pulling effort in the cored area becomes increasingly asymmetrical as the load inclination shifts from 0° to 2°, and then to 4° (Fig. 7). Under a load perfectly aligned with the coring axis (0°), in addition to the absence of stress asymmetry, transverse stresses ($\sigma_x$) at the bottom of the core cut are very small. These stresses also increase when the angle of inclination increases, especially at the bottom of the core. The largest stress imbalance, either for axial ($\sigma_y$) or transverse ($\sigma_x$) load, occurs within the load plane between points located at the tip of each slit and identified as A and B (Figs. 4 and 5), where the maximum and minimum stresses are found respectively.

Severity of the stress imbalance obviously depends on the misalignment magnitude. Based upon the data summarized in Table 3, a 4° misalignment theoretically induces a significant axial stress ($\sigma_y$) differential at the bottom of the core. Stress distributions were calculated for different core depths and angles of inclination. As the value of the angle of inclination increases, the maximum axial stress increases at a progressively increasing rate (Fig. 8). Besides, it can be observed that the influence of the depth of coring is minor up to an inclination angle of approximately 10°, beyond which the axial stress imbalance appears to increase with the depth of coring. This is in accordance with Cleland’s findings.¹⁵

At point A, a misalignment angle of 2° induces maximum axial ($\sigma_y$) stress increases of 6 and 9%, for core depths of 15 and 30 mm [1.18 and 2.36 in.] respectively, while a misalignment angle of 4° causes the axial stresses to increase by 14 and 19% for core depths of 15 and 30 mm [1.18 and 2.36 in.] respectively. As a simple first-order assumption, it can be inferred that corresponding the pull-off strength values are reduced by 7 and 13% for a coring depth of 15 mm [1.18 in.] and by 8 and 16% for a coring depth of 30 mm [2.36 in.].
It should be noted that the actual numerical results are dependent on the modelling assumptions and assumed material properties. For instance, the use of different E modulus values would have yielded different results.

**EXPERIMENTAL RESULTS AND DISCUSSION**

The effect of misalignment was evaluated experimentally through pull-off experiments. The test results yielded under different conditions are summarized in Table 5, along with the results of direct tensile strength tests performed for comparison purposes on 50-mm (1.97-in.) cores extracted from the test slabs. The direct tensile strength results recorded for the three mixtures are relatively close to each other and, contrary to the compressive strength data (Table 3), do not exhibit a systematic increase with the w/cm reduction. It is not uncommon, given the non-linear relationship between tensile and compressive properties of concrete and the inherently more variable character of tensile strength determination.

In Table 5, it can be observed that for given test conditions, the average recorded pull-off strength values for the three investigated concrete mixtures are also very close. Besides, based on the comparison with direct tensile data for 0° misalignment and the shallowest core depth, the results yielded in the pull-off experiment provide a reliable appraisal of the actual substrate tensile strength.

In general, with regards to the influence of test misalignment, the pull-off test results exhibit trends that do not stand out as clearly as in the numerical analysis, owing for one to the respective tensile testing and material variabilities, which are not taken into account in
deterministic calculations such as those performed in this study. In fact, the coefficients of
variation of the recorded pull-off results, which are summarized in Table 7, are of the same
order of magnitude as the calculated strength reduction due to testing misalignment (7 and
13% for 2° and 4° misalignments, and 15-mm cores; 8 and 16% for 2° and 4° misalignments,
and 30-mm cores). It thus appears normal to have less definite trends. Besides, as found again
in the simulations, a decrease in recorded pull-off strength values is systematically observed
when increasing the core depth from 15 mm [1.18 in.] to 30 mm [2.36 in.]. For the 30-mm
coring depth series latter, the effect seems to overshadow the influence of misalignment.

In Fig. 9, the experimental pull-off results of all three tested mixture were averaged for each
coring depth / misalignment combination and compared to the theoretical values, which were
determined based upon the simulation results. It can be seen that the experimental results are
quite close to the predicted values for the 15-mm deep coring series, while in the case of the
30-mm deep series, the recorded values seem to be little affected by misalignment and exceed
slightly the calculations. Overall, it appears that the pull-off simulations provide a satisfactory
level of accuracy for practical purposes, allowing a realistic prediction on the conservative
side.

As for the type of failure encountered in the test program, more than 89% of the failures
occurred at the bottom of the core, with only a few failures (6%) recorded in the body of the
core. Detailed examinations of the fracture surfaces revealed interesting behavior:
irrespective of the concrete mixture, the proportion of aggregate failures across the fracture
surfaces in the test series performed with a coring depth of 15 mm [1.18 in.] was found to be
systematically higher than in the 30-mm [2.36-in.] coring depth series. This observation is
consistent with the higher pull-off tensile strength recorded in the former.

Conversely, the proportion of aggregate failures did not appear to be significantly affected by test misalignment.

CONCLUSIONS

On the basis of the results of the numerical analysis and experimental results, the following conclusions can be drawn:

• up to a certain misalignment limit angle assumed to be detectable by the average human eye (4° in the present study), load and coring misalignments were not found to yield significantly different stress fields and, for practical calculation purposes, they can be addressed in a similar fashion;

• results of simulations revealed that a distorted stress field is induced by pulling-off testing misalignment, resulting in stress concentrations in an area at the bottom of the core slit: a 2° misalignment yield maximum stress increases of 6 and 9 % respectively for 15-mm and 30-mm coring depths, and the corresponding increases resulting from a 4° misalignment reach 14 and 19%;

• the experimental pull-off test program results are overall consistent with the theoretical calculations, although the observed trends are not as clear, owing to the experimental variability and to the added influence of the coring depth;

• the simulation results provide a conservative but realistic lower bound limit for evaluation the influence of misalignment upon pull-off test results: a 2° misalignment can be expected to yield a pull-off strength reduction of 7 to 9 % respectively for 15-mm [1.18-in.] and 30-mm [2.36-in.] coring depths, and the corresponding decrease
resulting from a 4° misalignment reach between 13 and 16%;

• as for the failure mode, it can be concluded that within 4°, testing misalignment does not significantly change the failure mode characteristics.

From a practical standpoint, the results generated in this study indicate that when specifying a pull-off strength limit in the field, the value should be increased (probable order of magnitude: 15%) to take into account the potential reduction due to testing misalignment.

ACKNOWLEDGMENTS

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  d) Positioning of the pull-off test device
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  a) 0° misalignment / 15 mm core
  b) 0° misalignment / 30 mm core
  c) 2° misalignment / 15 mm core
d) 2° misalignment / 30 mm core

e) 4° misalignment / 15 mm core

f) 4° misalignment / 30 mm core

Fig. 7–Axial stress ($\sigma_y$) distribution for misalignment angles of 0°, 2° and 4° and coring depths of 15 and 30 mm.

Fig. 8–Theoretical axial stress ($\sigma_y$) amplification as a function of the misalignment angle of inclination and coring depth in a pull-off experiment.

Fig. 9–Comparison of predicted and experimental pull-off test results.
Table 1–Numerical and experimental test program variables

<table>
<thead>
<tr>
<th>Test parameter</th>
<th>Numerical simulations</th>
<th>Laboratory tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Monolithical slab</td>
<td>Monolithical slab</td>
</tr>
<tr>
<td>Coring axis inclination angle</td>
<td>0°, 2°, 4°</td>
<td>0°, 2°, 4°</td>
</tr>
<tr>
<td>Pulling force inclination angle</td>
<td>0°, 2°, 4°</td>
<td>0°</td>
</tr>
<tr>
<td>Core depth</td>
<td>15 mm, 30 mm</td>
<td>15 mm, 30 mm</td>
</tr>
</tbody>
</table>

Note: 1 mm = 0.03937 in.

Table 2–Concrete mixture compositions (Part I)

<table>
<thead>
<tr>
<th>Constituent / characteristic</th>
<th>Mixture</th>
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<tr>
<td></td>
<td>C30/37</td>
</tr>
<tr>
<td>CEM I 52,5N</td>
<td>[kg/m³]</td>
</tr>
<tr>
<td>Water</td>
<td>[kg/m³]</td>
</tr>
<tr>
<td>Crushed sand (0-2 mm)</td>
<td>[kg/m³]</td>
</tr>
<tr>
<td>Crushed limestone (2-8 mm)</td>
<td>[kg/m³]</td>
</tr>
<tr>
<td>Crushed limestone (8-14 mm)</td>
<td>[kg/m³]</td>
</tr>
<tr>
<td>Crushed limestone (14-20 mm)</td>
<td>[kg/m³]</td>
</tr>
<tr>
<td>W/C</td>
<td></td>
</tr>
</tbody>
</table>

Note: 1 kg/m³ = 1.685 lb/ft³; 1 mm = 0.03937 in.

Table 3–Compressive strength determination at 28 days (Part I)

<table>
<thead>
<tr>
<th>Concrete mixture</th>
<th>$f_{c,28d}$ [MPa]</th>
<th>Standard deviation $s_n$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C30/37</td>
<td>50.1 (39.6)</td>
<td>1.47</td>
</tr>
<tr>
<td>C40/50</td>
<td>60.9 (48.1)</td>
<td>1</td>
</tr>
<tr>
<td>C50/60</td>
<td>65.4 (51.7)</td>
<td>1.90</td>
</tr>
</tbody>
</table>

$^{1}$ Tests performed on 150×150×150 mm cubes per EN 12390-3; each data corresponds to the average of 5 test results; equivalent 150×300-mm cylinder strength in parentheses.

Note: 1 MPa = 145.0 psi.
Table 4–Calculated pull-off test stress differentials induced by a 4° misalignment (7.85 kN [1,77 lb])

<table>
<thead>
<tr>
<th>Testing conditions</th>
<th>Point A</th>
<th>Point B</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$\sigma_x$ [MPa]</td>
<td>$\sigma_y$ [MPa]</td>
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<tr>
<td>4° – core misalignment</td>
<td>1.1</td>
<td>3.2</td>
</tr>
<tr>
<td>15 mm coring depth</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4° – load misalignment</td>
<td>1.4</td>
<td>3.2</td>
</tr>
<tr>
<td>30 mm coring depth</td>
<td></td>
<td></td>
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</table>

Note: 1 MPa = 145.0 psi; 1 mm = 0.03937 in.

Table 5–Axial stress ($\sigma_y$) amplification calculated as a function of the misalignment angle of inclination and coring depth in a pull-off experiment.

<table>
<thead>
<tr>
<th>Misalignment angle (°)</th>
<th>Maximum axial stress ($\sigma_y$) amplification [%]</th>
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<tbody>
<tr>
<td></td>
<td>Core depth [mm]</td>
</tr>
<tr>
<td></td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
</tr>
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<td>4</td>
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<td>15</td>
<td>57</td>
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<td>20</td>
<td>89</td>
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Note: 1 mm = 0.03937 in.
### Table 6–Direct tensile test and pull-off test results

<table>
<thead>
<tr>
<th>Concrete mixture</th>
<th>Test nr</th>
<th>Avg. direct tensile strength&lt;sup&gt;1&lt;/sup&gt; [MPa]</th>
<th>Pull-off strength [MPa]</th>
<th>Core depth</th>
<th>Misalignment angle</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15mm</td>
<td>0° 2° 4°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30mm</td>
<td>0° 2° 4°</td>
</tr>
<tr>
<td>C30/37</td>
<td>1</td>
<td>3.6</td>
<td>3.8 3.5 3.2</td>
<td>3.6 3.0 3.6</td>
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<td>3.6</td>
<td>3.4 3.3 3.2</td>
<td>3.0 2.9 2.4</td>
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<tr>
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<td>3</td>
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<td>3.8 3.8 3.8</td>
<td>3.2 3.0 2.8</td>
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<td>4</td>
<td>3.8</td>
<td>3.2 3.6 3.6</td>
<td>3.6 3.0 3.4</td>
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<sup>1</sup> Test performed on 50-mm (2-in.) diameter cored cylinders; each data corresponds to the average of 5 test results.

Note: 1 MPa = 145.0 psi; 1 mm = 0.03937 in.

### Table 7–Variability of the pull-off strength data

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<tr>
<th>Concrete mixture</th>
<th>Pull-off strength COV (coeff. of variation) [%]</th>
<th>Core depth [mm]</th>
<th>Misalignment angle</th>
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</table>

Note: 1 mm = 0.03937 in.
Fig. 1–Sources of misalignment in a pull-off test.

a) Core axis inclination

b) Load inclination
Fig. 2–Influence of the load inclination (from Cleland et al.\textsuperscript{15}).
Fig. 3—Example of boundary conditions used in the analysis (case: pulling load with an angle of inclination 4°; core depth of 30 mm).
Fig. 4–Example of FEM mesh used in the analysis (case: pulling load with an angle of inclination 4°; core depth of 30 mm).

Fig. 5–Geometry and points (A and B) of analysis.
a) Special device for controlling the coring axis inclination

b) Slab positioning for coring at an angle of 4°

c) Dolly installation

d) Positioning of the pull-off test device

Fig. 6–Pull-off test preparation.
Fig. 7–Axial stress ($\sigma_y$) distribution for misalignment angles of 0°, 2° and 4° and coring depths of 15 and 30 mm.

Note: 1 MPa = 145.0 psi; 1 mm = 0.03937 in.
Fig. 8–Theoretical axial stress ($\sigma_y$) amplification as a function of the misalignment angle of inclination and coring depth in a pull-off experiment.

Fig. 9–Comparison of predicted and experimental pull-off test results.
List of symbols

1. Avg. = average value
2. Sn = Standard Deviation
3. EN = European Norm
4. W/C = Water to Cement ratio
5. FEM = Finite Element Analysis
6. MPa = MegaPascal (N/mm²)