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

L. Courard, B. Bissonnette, A. Garbacz, A. Vaysburd,
K. von Fay, G. Moczulski and M. Morency

Biography: *ACI Member* ***Luc Courard*** *is a Professor in the Department of Architecture, Geology, Environment and Constructions at the University of Liège, Belgium. He is a member of RILEM and Belgian Group of Concrete. ACI member* ***Benoît Bissonnette*** *is a Professor in the Department of Civil Engineering at Laval University (Quebec City (QC), Canada). He is a member of ACI Committees 223, Shrinkage-Compensating Concrete; 364, Rehabilitation.* ***Andrzej Garbacz*** *is a Professor in the Department of Building Materials Engineering at Warsaw University of Technology, senior member of RILEM. FACI* ***Alexander M. Vaysburd*** *is Principal of Vaycon Consulting, Baltimore, MD and an Associate Professor at Laval University. He is a member of ACI Committees 213, Lightweight Aggregate and Concrete; 364, Rehabilitation; 365, Service Life Prediction; and 546, Repair of Concrete. In 1996, he was awarded the ACI Wason Medal for Most Meritious Paper. In 2000, he received both the ACI Cedric Wilson Award and the ACI Construction Award. ACI member* ***Kurt von Fay*** *is a Civil engineer at the U.S. Bureau of Reclamation (Technical Service Center / Materials Engineering and Research Lab located in the Denver Federal Center). He is a member of ACI Committees 235, Electronic Data Exchange; 364, Rehabilitation; SDC-09, Crack Reduction Initiative; and SDC-43, Vision 2020 Initiative.* ***Grzegorj Moczulski*** *is a research engineer in Warsaw University of Technology where he received a MS in civil engineering.* ***Maxim Morency*** *is General Manager at IBB Rheology Inc. in Quebec City (QC), Canada. He received his BS and MS (Structural engineering –*

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[1]. 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.[2,3]

Concrete repair process usually involves the removal of deteriorated or contaminated material and surface preparation prior to application of a repair material.[4] 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.[5-11]

The pull-off test is a simple and effective test for evaluating both the mechanical integrity of the substrate prior to repair[12, 13] 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[12, 14], 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.[15,16,17,18,19] Geometry of the dolly and core drilling depth into the substrate were also found to be critical factors when testing for bond in repair systems.[16]

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[20]: 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.[13]

Austin et al.[14] 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.[6] Cleland and Long[15] 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:

$$F_{lr} = \frac{1}{[1-(\frac{8 \cdot \tan \alpha}{D}) \cdot y]} \qquad (1)$$

where α, 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.

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.

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 (monolithical), 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 programs were 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[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[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/in^2];
- Poisson ratio: 0.20;
- Density: 2500 kg/m^3 [4215 lb/yd^3];
- 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)).[12] 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 (σ_x), 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 (σ_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 (σ_y) or transverse (σ_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 (σ_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 (σ_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

The authors are grateful to the ACI Concrete Research Council, which provided financial support to this study as part of an international research project entitled "*Development of Specifications and Performance Criteria for Surface Preparation Based on Issues Related to Bond Strength*". Support was also provided by the Government of Poland (MNiSW), the Regional Government of Wallonia (Belgium), and the Government of Quebec (Canada) through bilateral scientific cooperation programs. G. Moczulski performed the experimental and modeling programs at the University of Liege, Belgium, through European Union Student Erasmus exchange program.

REFERENCES

1. Vaysburd, A. M., and Emmons, P. H., "How to Make Today's Repairs Durable for Tomorrow – Corrosion Protection in Concrete Repair," *Construction and Building Materials,* **14**(4), 2000, pp. 189-197.
2. Courard, L., "Parametric Study for the Creation of the Interface between Concrete and Repair Products," *Materials and Structures*, **33**(225), 2000, pp. 65-72.

3. Courard, L.; Michel, F.; Schwall, D.; Van der Wielen, A.; Garbacz A.; Piotrowski T.; Perez, F.; and Bissonnette, B., "Surfology: Concrete Substrate Evaluation prior to Repair," *Materials Characterization: computational methods and experiments IV* (A. Mammoli and C. A. Brebbia eds., Wessex Institute of Technology Press), The New Forest (U.K.), June 17-19, 2009, pp. 407-16.
4. Bissonnette, B.; Courard, L.; Vaysburd, A. M.; and Bélair, N., "Concrete Removal Techniques: Influence on Residual Cracking and Bond Strength," *Concr. Int.*, **28**(12), 2006, pp. 49-55.
5. Ohama, Y.; Demura, K.; Nagao, H.; and Ogo, T., "Adhesion of Polymer Modified Mortars to Ordinary Cement Mortar by Different Methods, Adhesion between Polymers and Concrete, Bonding-Protection-Repair," Proceedings ISAP 86 *Adhesion between polymers and concrete*, (H.R. Sasse, Chapman and Hall, London), 1986, pp. 179-229.
6. Hindo, K. L., "In-Place Bond Testing and Surface Preparation of Concrete," Concrete International, **12**(4), 1990, pp. 46-48.
7. Cleland, D. J.; Naderi, M.; and Long, A. E., "Bond Strength of Patch Repair Mortars for Concrete," in Proceedings ISAP 86 *Adhesion between polymers and concrete*, (H.R. Sasse, Chapman and Hall, London), 1986, pp. 235-244.
8. Naderi, M.; Cleland, D. J.; and Long, A. E., "In Situ Test Methods for Repaired Concrete Structures," Proceedings ISAP 86 *Adhesion between polymers and concrete,* (H.R. Sasse, Chapman and Hall, London), 1986, pp. 707-718.
9. Austin, S. A., and Robins, P. J., "Development of a Patch Test to Study the Behaviour of Shallow Concrete Patch Repairs," *Concrete Research*, **45**(164), 1993, pp. 221-229.
10. Long, A. E. "A Review of Methods of Assessing the In-Situ Strength of Concrete,"

Keynote paper NDT 83 (Heathrow, London, England), Nov. 16-17, 1983, 16 p.

11. Bungey, J. H., and Soutsos, M. N., “Reliability of Partially-Destructive Tests to Assess the Strength of Concrete on Site,” *Construction and Building Materials*, **15**, 2001, pp. 81-92.
12. Courard, L., and Bissonnette, B. “Adaptation of the Pull-off Test for the Evaluation of the Superficial Cohesion of Concrete Substrates in Repair Works: Analysis of the Test Parameters,” *Mater. Struct.*, **37**(269), 2004, pp. 342-350.
13. Bungey, J. H., and Madandoust, R. “Factors Influencing Pull-off Tests on Concrete,” *Magazine. Concrete Research,* **44**(158), 1992, pp. 21-30.
14. Murray, A. McC., and Long, A. E., “A Study of the In-Situ Variability of Concrete Using the Pull-off Test Method,” Proc. Instn Civ. Engrs, Part 2, (83), 1987, pp. 731-745.
15. Cleland, D. J., and Long, A. E. “The Pull-off Test for Concrete Patch Repairs”, Proc. Instn Civ. Engrs Structs & Bldgs, **122**(11), 1997, pp. 451-460.
16. Austin, S., Robins, P., and Pan, Y., “Tensile Bond Testing of Concrete Repairs,” *Mater. Struct.*, **28**, 1995, pp. 249-259.
17. Cleland, D. J.; Yeoh, K. M.; and Long, A. E., “The Influence of Surface Preparation Method on the Adhesion Strength of Patch Repairs for Concrete”, *Proceedings of the 3rd Colloquium on Materials Science and Restoration*, (Esslingen, Germany), 1992, pp. 858-871.
18. Czarnecki, L., “Adhesion – a Challenge for Concrete Repair,” *ICCRRR08 International Congress on Concrete Repair, Reinforcement and Retrofitting* (Alexander *et al*. eds., 2009 Taylor & Francis Group, London), Cape Town, 2008, pp. 935-940.

19. Vaysburd, A. M., and McDonald, J. E., “An Evaluation of Equipment and Procedures for Tensile Bond Testing of Concrete Repairs,” *US Army Corps of Engineers*, Technical Report REMR-CS-61, 1999, 65 p.
20. Moczulski, G., Garbacz, A., and Courard, L., “Evaluation of the Effect of Load Eccentricity on Pull-off Strength,” *ICCRRR08 International Congress on Concrete Repair, Reinforcement and Retrofitting* (Alexander *et al*. eds., 2009 Taylor & Francis Group, London), Cape Town, 2008, pp. 1017-22.
21. Collin, F, “Thermo-hydro-mechanical coupling in partialy saturated soils and soft rocks”, PhD thesis, University of Liège, 2002.
22. Gerard, P., Charlier, R., Chambon, R. and Collin, F. “Influence of evaporation and seepage on the convergence of a ventilated cavity”, *Water Ressources Research*, 40(7), 2008,W00C02.

TABLES AND FIGURES

List of Tables:

List of Figures:

d) 2° misalignment / 30 mm core
e) 4° misalignment / 15 mm core
f) 4° misalignment / 30 mm core

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

Fig. 8–Theoretical axial stress (σ_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

Test parameter	Numerical simulations	Laboratory tests	
	Monolithical slab	Monolithical slab	Repaired slab
Coring axis inclination angle	0°, 2°, 4°	0°, 2°, 4°	0°, 2°, 4°
Pulling force inclination angle	0°, 2°, 4°	0°	0°
Core depth	15 mm, 30 mm	15 mm, 30 mm	100 mm

Note: 1 mm = 0.03937 in.

Table 2–Concrete mixture compositions (Part I)

Constituent / characteristic		Mixture		
		C30/37	C40/50	C50/60
CEM I 52,5N	[kg/m^3]	275	325	375
Water	[kg/m^3]	192	186	182
Crushed sand (0-2 mm)	[kg/m^3]	765	729	676
Crushed limestone (2-8 mm)	[kg/m^3]	255	230	206
Crushed limestone (8-14 mm)	[kg/m^3]	569	576	601
Crushed limestone (14-20 mm)	[kg/m^3]	390	401	412
W/C		0.70	0.57	0.49

Note: 1 kg/m^3 = 1.685 lb/yd^3; 1 mm = 0.03937 in.

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

Concrete mixture	$f_{c\ 28d}$ [1] [MPa]	Standard deviation s_n [MPa]
C30/37	50.1 (39.6)	1.47
C40/50	60.9 (48.1)	1
C50/60	65.4 (51.7)	1.90

[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])

Testing conditions	Point A		Point B	
	σ_x [MPa]	σ_y [MPa]	σ_x [MPa]	σ_y [MPa]
4° – **core** misalignment 15 mm coring depth	1.1	3.2	0.8	2.2
4° – **load** misalignment 30 mm coring depth	1.4	3.2	0.6	2.2

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

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

Misalignment angle (°)	Maximum axial stress (σ_y) amplification [%]	
	Core depth [mm]	
	15	30
2	7	9
4	15	19
10	41	39
15	57	84
20	89	117

Note: 1 mm = 0.03937 in.

Table 6–Direct tensile test and pull-off test results

Concrete mixture	Avg. direct tensile strength[1] [MPa]	Test nr	Pull-off strength [MPa]					
			core depth					
			15mm			30mm		
			Misalignment angle					
			0^{O}	2^{O}	4^{O}	0^{O}	2^{O}	4^{O}
C30/37	3.6	1	3.8	3.5	3.2	3.6	3.0	3.6
		2	3.4	3.3	3.2	3.0	2.9	2.4
		3	4.1	3.8	3.8	3.2	3.0	2.8
		4	3.8	3.2	3.6	3.6	3.0	3.4
		5	3.6	3.7	3.8	2.7	2.6	2.5
		6	A.F.	3.2	3.5	2.6	3.0	A.F.
		Avg.	3.8	3.4	3.5	3.1	3.0	2.8
C40/50	3.9	1	3.7	3.3	3.4	2.9	2.9	3.4
		2	4.1	3.9	3.8	3.3	3.1	3.6
		3	4.0	3.2	3.7	3.7	2.9	2.9
		4	A.F.	A.F.	A.F.	3.0	2.5	A.F.
		5	3.6	3.4	2.8	A.F.	3.6	3.3
		6	3.9	3.8	3.3	2.6	3.2	3.2
		Avg.	3.9	3.4	3.4	3.0	3.0	3.3
C50/60	3.5	1	4.0	3.8	3.0	3.5	2.8	2.4
		2	3.7	3.3	3.6	3.6	3.0	2.3
		3	3.9	4.2	3.7	3.7	3.3	3.1
		4	3.3	3.4	3.3	3.2	A.F	3.4
		5	4.1	4.0	3.5	3.1	2.9	3.3
		6	4.4	4.0	3.3	2.8	3.5	3.1
		Avg.	3.9	3.9	3.4	3.3	3.0	3.1

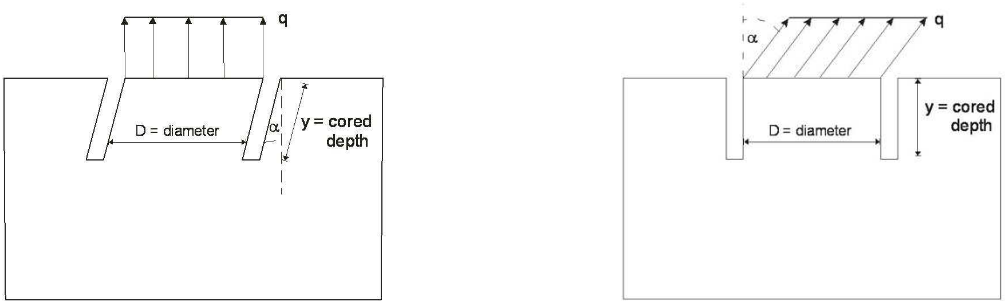
[1] Test performed on 50-mm (2-in.) diameter cored cylinders; each data corresponds to the average of 5 test results.

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

Table 7–Variability of the pull-off strength data

Concrete mixture	Pull-off strength COV (coeff. of variation) [%]					
	Core depth [mm]					
	15			30		
	Misalignment angle					
	0°	2°	4°	0°	2°	4°
C30/37	8	9	9	13	7	17
C40/50	5	9	12	13	13	9
C50/60	10	10	9	9	10	17

Note: 1 mm = 0.03937 in.



a) Core axis inclination *b) Load inclination*

Fig. 1–Sources of misalignment in a pull-off test.

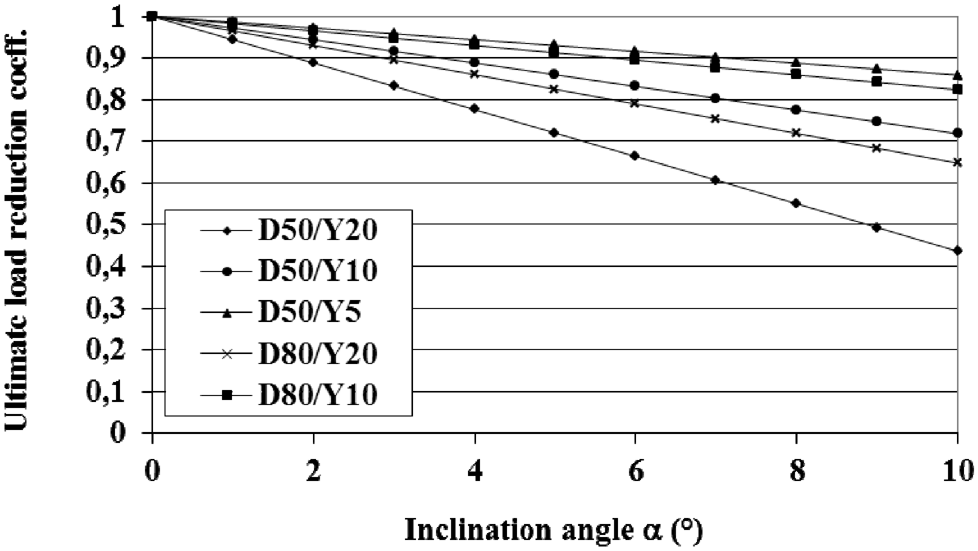
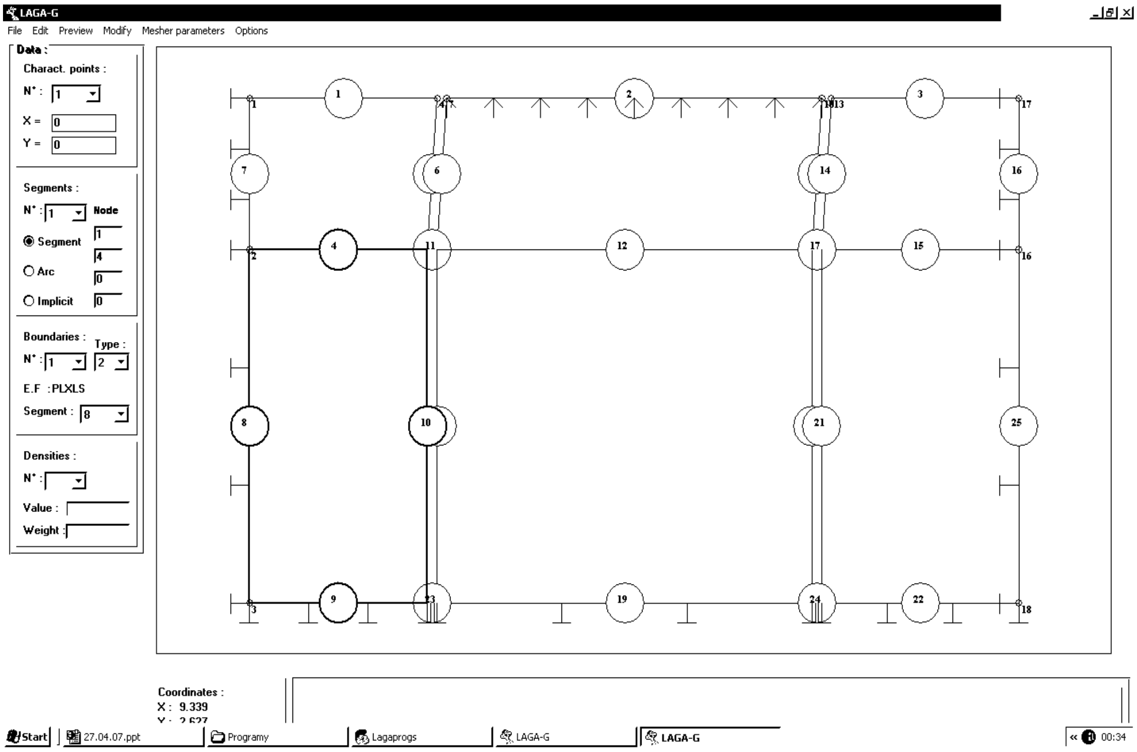


Fig. 2–Influence of the load inclination (from Cleland et al.[15]).



Data :

Charact. points :
N° : 1
X = 0
Y = 0

Segments :
N° : 1
Node
● Segment 1
4
○ Arc 0
○ Implicit 0

Boundaries :
N° : 1
Type : 2
E.F : PLXLS
Segment : 8

Densities :
N° :
Value :
Weight :

Coordinates :
X : 9.339
Y : 2.627

Fig. 3–Example of boundary conditions used in the analysis (case: pulling load with an angle of inclination 4°; core depth of 30 mm).

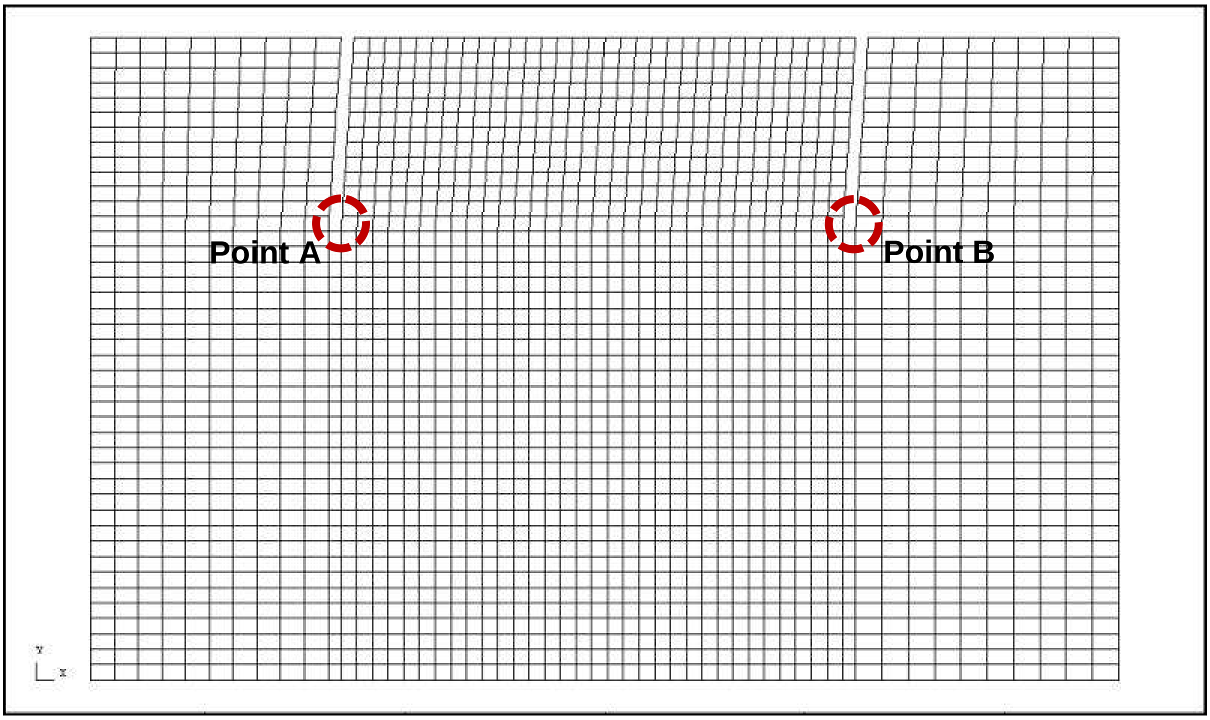


Fig. 4–Example of FEM mesh used in the analysis (case: pulling load with an angle of inclination 4°; core depth of 30 mm).

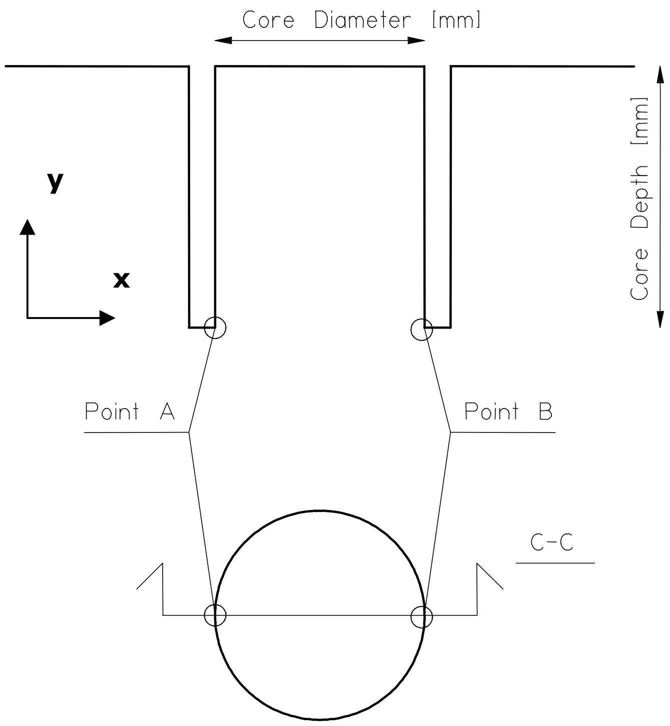


Fig. 5–Geometry and points (A and B) of analysis.

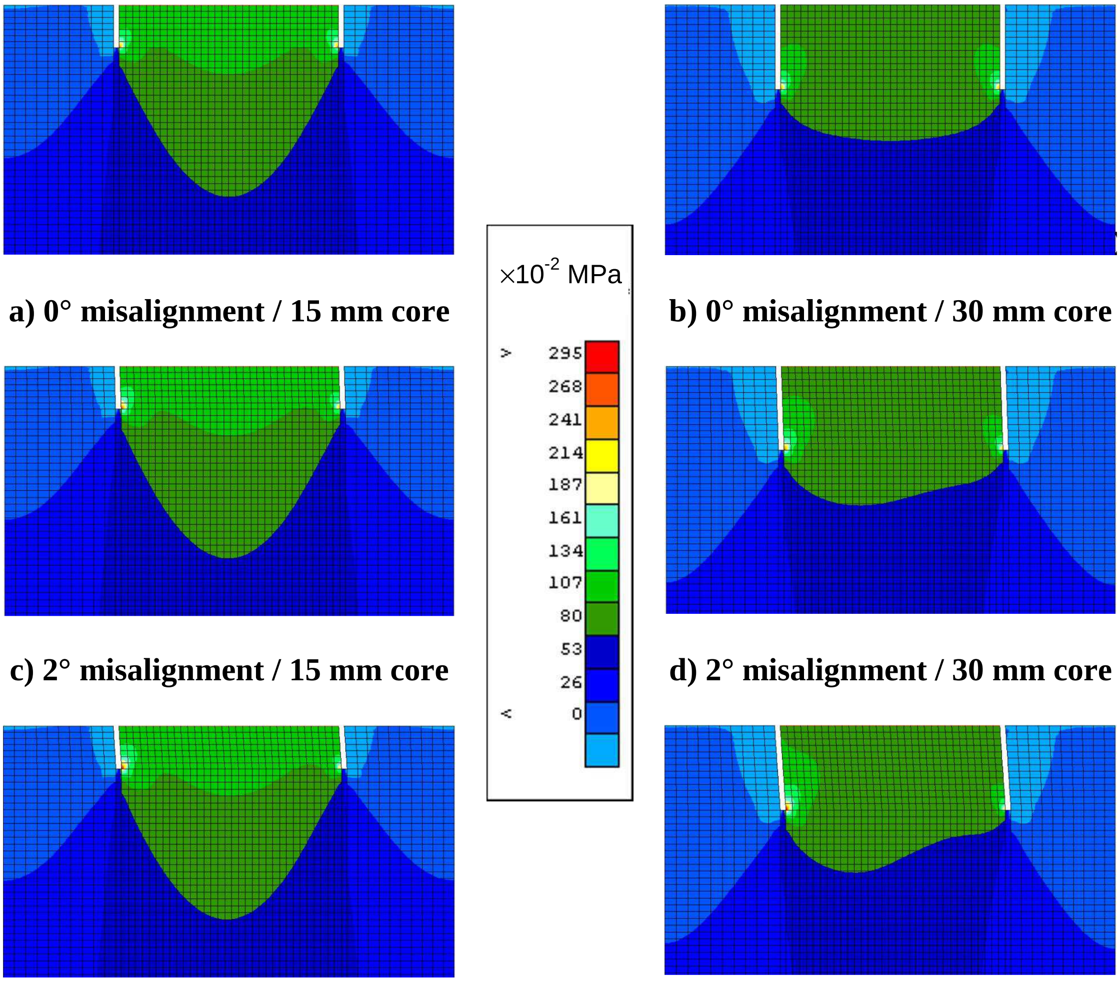
a) Special device for controlling the coring axis inclination

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.



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

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

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

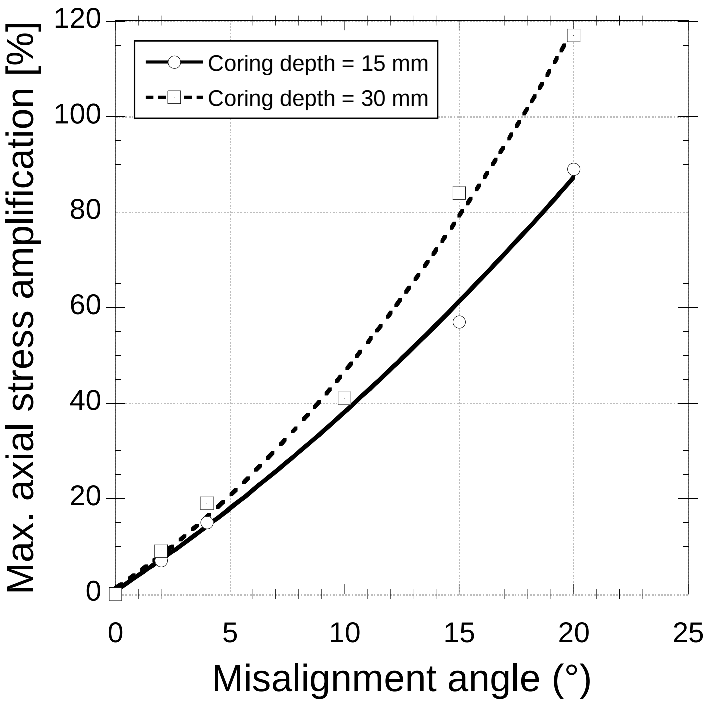


Fig. 8–Theoretical axial stress (σ_y) amplification as a function of the misalignment angle of inclination and coring depth in a pull-off experiment.

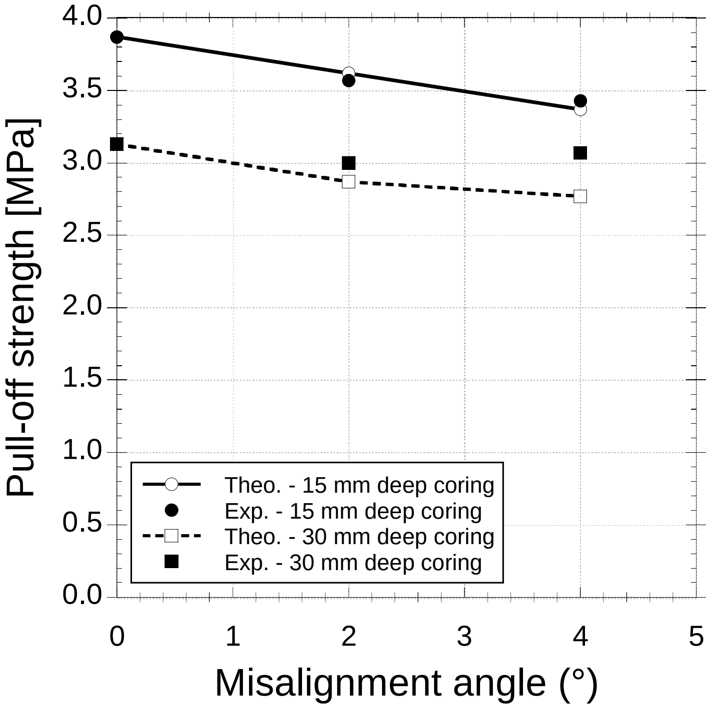


Fig. 9–Comparison of predicted and experimental pull-off test results.

List of symbols

Avg. = average value
Sn = Standard Deviation
EN = European Norm
W/C = Water to Cement ratio
FEM = Finite Element Analysis
MPa = MegaPascal (N/mm^2)