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DESIGN OF BOND STRENGTH TESTING METHOD OF CONCRETE LAYERS FOR CREATING A MATERIAL MODEL

Marek Kříž, Michaela Frantová*, Václav Wudi, Petr Štemberk

Czech Technical University in Prague, Faculty of Civil Engineering, Department of Concrete and Masonry Structures, Thákurova 7, 166 29 Prague 6, Czech Republic

* corresponding author: michaela.frantova@fsv.cvut.cz

Abstract. The need to determine the bond strength of concrete layers in structural modeling is quite frequent and often encounters a lack of relevant experimental data due to the large number of variables which affect the bond strength. This article describes an experimental method that makes it possible to obtain the experimental data necessary for subsequent modeling of multi-layered concrete composite structures. The experiment is designed to be applicable both to laboratory specimens with defined properties and to samples taken from existing structures. The advantage of this method is its simplicity, minimal equipment requirements, and repeatability. The three-layer specimens, representing a sandwich wall, allow the study of the influence of the age and quality of the concrete on the bond strength, and through image analysis, provide valuable information on deformation, interlayer slip, and crack formation. The results of the experiment may contribute to the determination of a bond strength diagram for multi-layered walls, which can be integrated into software tools for comprehensive structural analyses.

Keywords: Bond strength, shear strength, cohesion of concrete layers, shear stress testing methods, image analysis.

1. Introduction

The majority of reinforced concrete structures cannot be cast all at once, and for various reasons, the concreting process needs to be interrupted during construction. At the point where concreting is interrupted, a construction joint is formed, where concrete from different casting sessions, theoretically of the same quality, but of different ages (and thus in different phases of hydration), meet. When designing and analyzing reinforced concrete structures, we assume that the material properties of the concrete remain constant throughout the structure and also model it as a whole. However, Figure 1 shows an example of core drillings through a construction joint in a concrete wall several decades old, where it is clear that the assumption of perfect bond at the construction joint is not correct. The need to understand the bond strength between layers of concrete of different ages arises in the repair of degraded or otherwise damaged structures, in structural strengthening, or in monolithic-precast and sandwich constructions.

Figure 1. Horizontal construction joint during concreting (the core on the left disintegrated by itself upon removal from the structure).

When strengthening structures or designing monolithic-precast constructions, it is crucial to know the shear strength of the bond at the interface between concrete layers of different ages. The interaction between the individual layers of the structure plays a significant role in the model used for the structural analysis. If we design sandwich structures without connecting elements, the bond strength is always a key factor in the calculation.

The bond strength between concrete layers can be measured in various ways. Tests differ in terms of loading type, types of samples attachment, interface angle, etc. Each testing type offers specific advantages and disadvantages. A typical problem with shear tests is the inability to create pure shear stress in the sample; in addition to shear stress, the interface is often subjected to torsional moments or compression. A common disadvantage of most tests (see Chapter 3) is the need for specific laboratory equipment, the complexity of the tests, or the inability to repeat them. The testing method we propose for measuring bond strength between concrete layers reduces these disadvantages, does not require specific laboratory equipment, and allows for the production of a larger number of test sets.

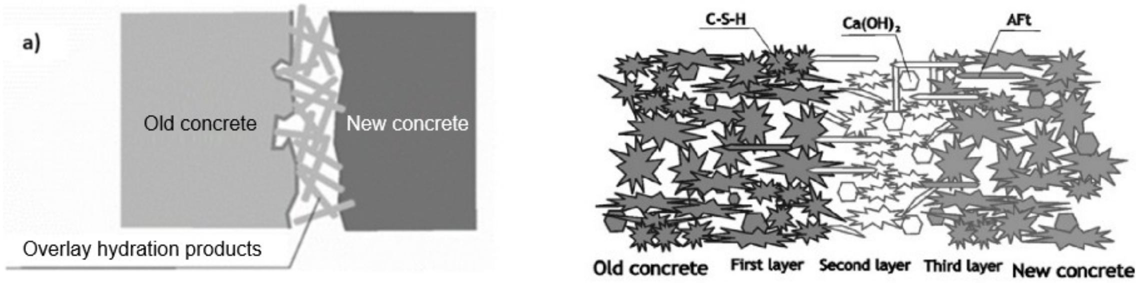

FIGURE 2. a) Macroscopic view of the transition zone, b) Microscopic view of the transition zone [1].

2. Methods of measuring bond strength

The bond strength between older and newly placed concrete depends on the adhesion of the fresh concrete mix to the surface of the older concrete, that is, on the ability of the mix to adhere perfectly to the surface. After the fresh concrete mix hardens, an interfacial zone forms at the interface of the layers. The resulting interfacial zone has similar properties to the interfacial transition zone (ITZ) between aggregate and hydrated cement paste and is weakened due to the so-called wall effect (Figure 3), in a similar way to how the ITZ between aggregate and cement paste is weakened. As a result of the wall effect, there are fewer hydration product particles and more pores at the interface, which are inversely proportional to the adhesion of the fresh concrete and reduce the contact area between the layers. Adhesion can be improved in various ways, such as surface treatment, optimizing the composition of the fresh concrete, and using additives and admixtures [2].

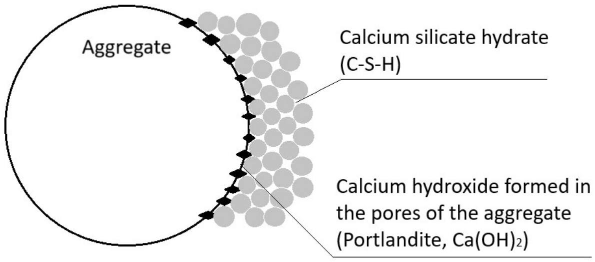

FIGURE 3. Schematic representation of the wall effect in the aggregate transition zone in concrete.

The contact surfaces between the older and newly placed concrete usually have different aggregate-to-cement ratios, water-cement ratios, and temperature developments during setting and hardening compared to the newly placed concrete. The failure at the interface between the older and newly placed concrete is similar to the failure in the transition zone at the interface between the aggregate and hardened cement paste [3].

The interfacial zone between the concretes, schematically illustrated in Figure 2 a), can be divided microscopically into three layers, as shown schematically in Figure 2 b).

The first layer can be called the penetration layer, located in the older concrete, and is composed mainly of C-S-H products with a smaller amount of AFt (ettringite) and $Ca(OH)_2$. The components of the fresh concrete react to a certain extent with the active components in the older concrete. The second layer is the weakest and most porous at the interface, containing $Ca(OH)_2$, highly oriented needle-shaped AFt crystals, and fewer C-S-H particles. This layer defines the low bond strength of the layers. The third layer is found in the new concrete and has almost the same microstructure as the new concrete, with individual AFt crystals oriented towards the interface.

Factors that influence the bond strength of concrete layers are those that affect the concrete mix during production, and they influence the bond strength at the material level on a molecular scale, such as additives, admixtures, water-cement ratio, optimal aggregate dosing, and the resulting concrete strength and shrinkage. The main admixture that improves the properties of the interface is silica fume (also known as microsilica), which fills the spaces at the interface of the concretes and participates in the hydration process [3]. Other admixtures with a positive impact on the concrete interface include blast furnace slag and fly ash; [4].

3. Methods for measuring bond strength

To determine the bond strength between the individual concrete layers, which we want to include in the numerical model for the structural analysis, it is necessary to experimentally verify the bond strength. Bond strength tests can be divided into predominantly shear and predominantly tensile types. The principle of each type of stress is schematically illustrated in Figure 4.

To achieve the appropriate type of stress in the experimental determination of bond strength, it is necessary to select the appropriate testing method. Various testing methods exist, each of which is influenced differently by factors that define the bond strength, such as the strength of the concrete, surface roughness, etc. The samples should be tested in a manner that simulates how they will predominantly be

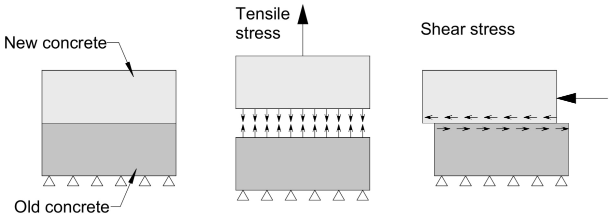

Figure 4. Main types of stresses at the interface for testing the bond strength.

stressed in the structure. It also depends on whether the test will be conducted on an existing structure or whether test samples will be specifically produced for the experiment [5].

In Figure 5 a) and b), tests perfomed in-situ, meaning directly on the structure, are schematically depicted. The torsion test shown in Figure 5 b) involves loading the sample with a torque, which subjects the interface only to shear stress. A challenge is expressing the resulting stress, as concrete is a brittle material that is neither entirely elastic nor purely plastic, making it difficult to accurately derive the shear stress from a known force.

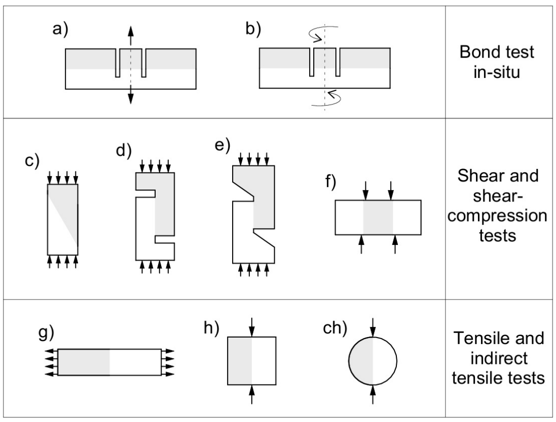

Figure 5. Schematic examples of commonly used testing methods.

Tests in the second row of the table labeled d), e), and f) are tests that induce „pure“ shear stress at the interface, while in case c), pressure is also present at the interface.

The last row of the table in Figure 5 illustrates tests where the tensile strength at the interface is determined, from which the shear strength is subsequently calculated [6]. The direct tensile strength testing method (g) is easy to perform both in terms of setup and loading. The challenge lies in securing the sample in the tensile device. The main advantage of this test is that it can be performed directly on the structure (in-situ), with the advantage over laboratory testing being that the sample is clamped only on one side for loading.

The Czech technical standards [7, 8] describe three types of tests for determining bond strength: indirect tensile strength test h), diagonal shear test c), and direct tensile strength test g), only for samples produced under laboratory conditions.

However, of the above tests, they best suited our goal of pure shear stress were the bond strength test on Z-shaped samples (d, e) [9] and the four-point shear test (f) [10]. Both tests are conducted in a press, where the samples are loaded with a vertical force that induces “pure” shear stress at the interface between the concrete layers until the sample fails. The advantage of the Z-shaped sample test is the presence of only one interface layer, while the disadvantage is the more complex shape of the samples. Another disadvantage of this test is that during loading, the sample can deform, leading to failure through mechanisms other than from pure shear stress. The four-point shear test is essentially the same loading scheme as the four-point flexural test, with the difference being that the loading forces and supports are aligned vertically, with only the interface of the test sample separating them. The disadvantage of this test is that there are two concrete layer interfaces, which may not fail simultaneously. The test is conducted in a press, with the sample being loaded vertically through distribution elements, such as a steel plate, which transfers the load to steel rods with a full square cross-section (Figure 6, b)).

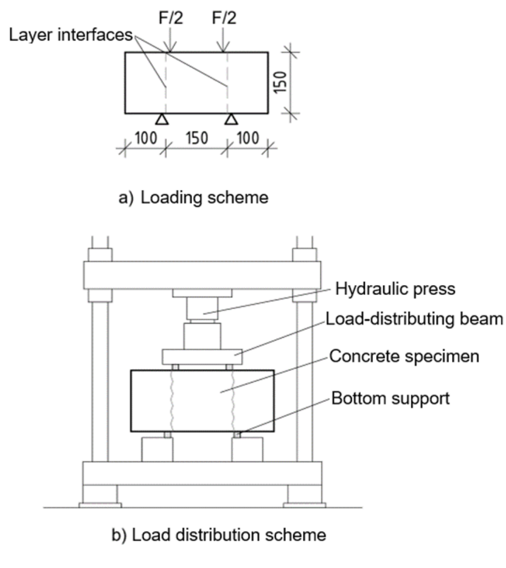

Figure 6. Sample loading scheme.

When testing bond strength, it is also necessary to evaluate the failure of the sample. Samples can fail in different ways, and if they fail in a way other than expected, they must be excluded from the overall analysis. The basic types of failure are schematically illustrated in Figure 7. Failure can occur at the interface between the layers, in the older concrete layer, or in the newly placed concrete. If failure repeatedly occurs in a place other than the interface, it means that the created interface is not the weakest point of the sample.

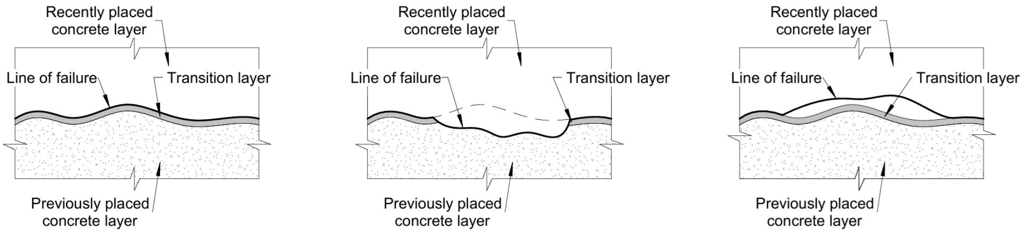

Figure 7. Possible types of failure in samples.

4. Design of a custom experiment

The aim of the experimental part was to design and perform a shear bond strength test that could be used both for samples manufactured under laboratory conditions and for samples taken from real multi-layered structures. The test should also be easily repeatable for the planned larger number of samples, which would include concrete of various ages, different strengths, and different surface roughness at the interface. Additionally, there was an effort to keep the experiment low-cost, using commonly available tools in a small laboratory and ensuring easy repetition of the test. The evaluation of the experiment consists of the measured load-bearing capacity at the interface of the concrete layers and the type of failure, as well as the possible slip, evaluated by image analysis.

Based on the evaluation of the advantages and disadvantages of bond strength tests described in the literature and in the previous chapter, a four-point shear test, performed in a standard loading press, was chosen as the starting point. The main advantage of this test is the ability to continuously record the slip at the layer interface under shear stress during the test and the simpler sample shape, which does not require the production of special molds. Another advantage is the easier demolding of the samples and the possibility of reusing the molds, unlike samples of more complex shapes. The overall dimensions of the samples were set at 40 × 40 × 160 mm because it was possible to use molds printed on a 3D printer with a silicone insert (Figure 8), which do not need to be oiled for easy demolding. Due to the smaller dimensions of the samples it was possible to simplify the loading. The loading scheme was simplified by removing local supports and adding continuous loading (Figure 9).

Figure 8. 3D printed mold with silicone insert.

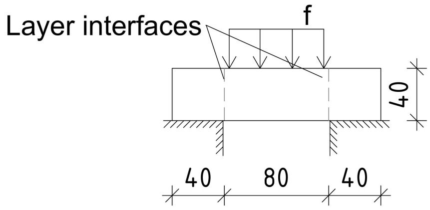

Figure 9. Sample loading scheme.

4.1. Test procedure

The samples are prepared in two separate concrete pours, which are time-separated. The molds were prepared in such a way as to simulate a sandwich construction, where the inner layer of concrete is cast onto the prefabricated outer layers concreted earlier. This means that the side parts of the samples were cast first. For casting the side parts, plastic blocks, printed on a 3D printer, were used as inserts to fill the centers of the molds. The inserts fit well into the molds and had the same dimensions (with only minor deviations due to 3D printing), as shown in Figure 10.

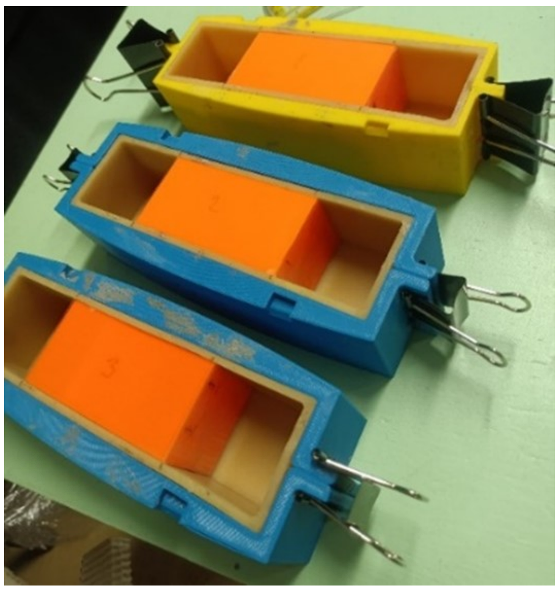

Figure 10. Preparation of molds for the first pouring.

The concrete pouring procedure is shown in Figure 11, where the left shows the first step of the pouring with the side parts of the sample cast, and the right shows the second step of the pouring with the inner (younger) part of the sample cast. The time

FIGURE 11. Top: first phase of pouring – older side parts of the sample. Bottom: second phase of pouring – complete sample with cast inner (younger) part.

gap between the two pouring steps was 10 days.

When preparing the samples, the possibility of producing samples with different interface roughness was also tested to determine the influence of interface roughness on bond strength. Three samples were produced, each with a shaped interface formed using a textured pad with projections (Figure 12 a), which were 0.2 mm high. The pad with different orientations of the projections (0°, 90°, and 45°) was inserted into the mold and attached (Figures 12 b, c, d).

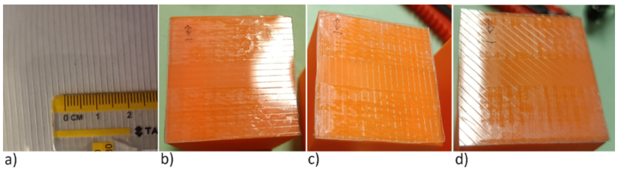

FIGURE 12. Forming the interface shape of the layers.

The concrete mixture was manually processed according to the recipe with aggregate fractions, considering the sample size, ranging from 0.6 to 1.2 mm. Fresh concrete was vibrated long enough in the molds to ensure that no air voids were present in the shaped interface. The resulting surface of the side parts of the samples is shown in Figure 13.

For the initial experiment design, it was necessary to make the slip between the layers in the concrete sample as clear as possible. Therefore, the samples were loaded 12 hours after casting the inner layer, at a time when the younger concrete had not yet reached its final strength, and the samples were still a bit malleable. The loading process of the sample in a manual hydraulic press is shown in Figure 14.

Before the actual loading, a pattern was drawn on the samples to serve as reference points for image

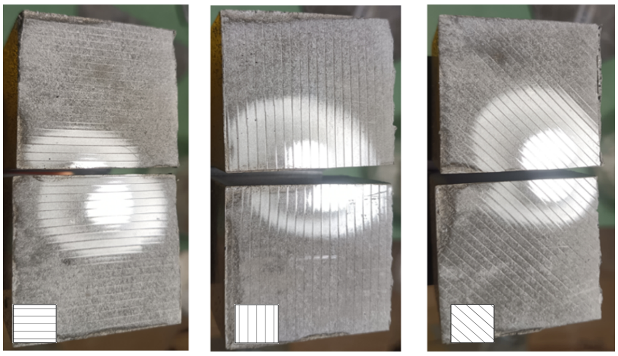

FIGURE 13. Side parts of the samples with shaped interface.

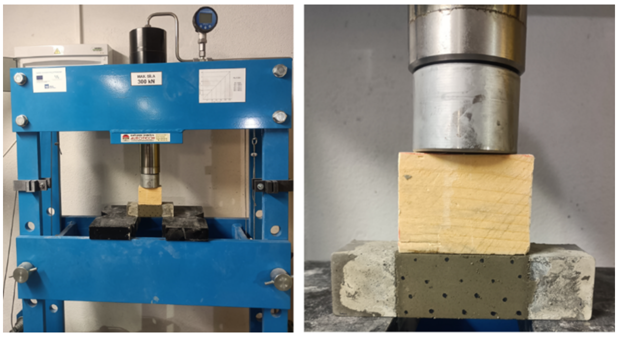

FIGURE 14. Loading in the hydraulic press.

analysis. To correctly use the image analysis, the well-lit sample had to be recorded with a slow-motion function (to capture the highest number of frames per second), as close to the sample as possible, perpendicular to the sample, and without moving the camera. It was also necessary to record the press, showing both the sample and the load readings, which would later be converted to force. The load was applied to the sample through a distribution wooden element 79 mm long, to apply pressure only to the center of the sample.

Figures 15 and Figure 16 show selected frames from the video recording (shot at 120 frames per second) during sample loading. The number above the frame represents the frame number, and the white vertical line marks the locations where cracks are forming. In Figure 15, the failure occurred simultaneously at both interfaces in the sample, which was an expected and correct failure pattern. In Figure 16, the failure was not entirely correct because the crack formed from the bottom surface upwards, and as the crack opened, the interface was improperly stressed, causing failure at only one interface.

To evaluate the experiment, a detailed analysis of possible sample failures was carried out, which is described and schematically illustrated in Figure 17.

4.2. IMAGE ANALYSIS

Image analysis, also known as image processing, is a process that involves analyzing digital images. The goal is to extract specific information from the images,

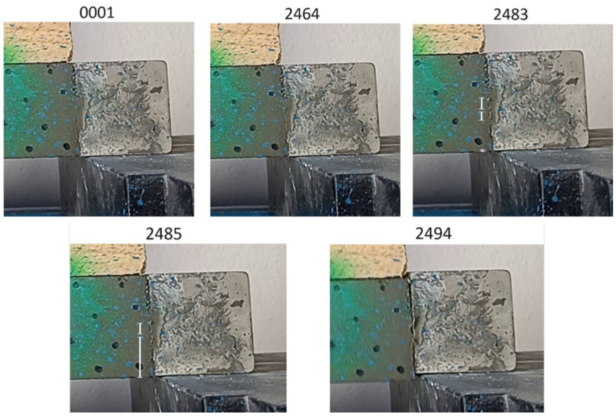

FIGURE 15. Correct failure of the sample (detailed section of the right side of the sample).

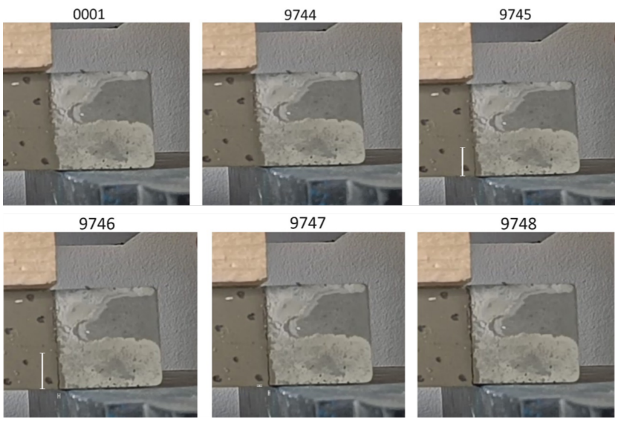

FIGURE 16. Incorrect failure of the sample (detailed section of the right side of the sample).

enhance their quality, and perform graphic modifications for specific purposes using tools available in a programming environment. Common tools for image analysis include noise removal, edge enhancement, resizing, contrast adjustment, pattern recognition, face recognition, segmentation (dividing the image into parts), and more. The sample needs to be captured with a camera as close as possible and perpendicular to the sample. To make operations with the recorded images easier, the sample should be properly illuminated and marked with any pattern. The number of frames per second, video resolution, and distance from the sample directly determine the accuracy of the method. During the analysis, an algorithm processes the large number of images automatically.

The video recording of the experiment was split into individual frames, which were then converted into a 3D matrix (three matrices for different base colors). This 3D matrix was transformed into a regular matrix representing a grayscale image. Each element of the matrix represented one pixel with a value from 0 to 255, depending on the shade of gray.

In the next step, the image was thresholded into binary form (black and white). Pixels with a value lower than the threshold were considered black, while those with a higher value were considered white. With

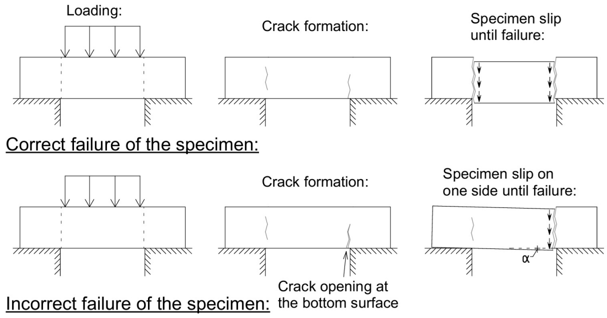

FIGURE 17. Comparison of correct and incorrect sample failures.

this modified image, edge detection was performed using a convolution matrix – see Figure 18.

The change in position of the detected edges across the frames will serve to quantify the deformation occurring at the interface between the sample layers. By capturing the movement of a specific point on the sample relative to the applied load, it will be possible to obtain a shear bond stress-strain curve for the layers.

5. CONCLUSION

In everyday construction practice, concrete structures are composed of concretes of different ages and qualities, which are connected, whether it is in monolithic-precast structures, when fresh concrete is added between two fully matured precast elements, or when it is needed to connect concretes of different ages, for example, during strengthening of existing structures. When designing such a structure, it is necessary to consider the interaction between different concrete layers in the model, as perfect bonding between the layers cannot be assumed. For modeling a sandwich structure, for example, it is imperative to clearly understand the degree of interaction and ideally to have sufficient experimental data on shear bond strength.

The purpose of this paper was to present an experimental method which can determine the shear bond strength of concrete layers without shear connectors. This experimental method can be used both for samples produced in the laboratory with well-defined boundary conditions and for samples taken from existing structures. The advantage of the proposed experimental method is its low requirements on equipment and easy repeatability. The three-layer samples can represent a simple sandwich wall, where the bond strength can be observed depending on factors such as the age of the concrete, the quality of the concrete in each layer, or the surface texture of the concrete layers. By utilizing image analysis, this experimental method can provide not only the final bond strength but also the deformation progression, slip between layers, and crack formation and propagation.

From the proposed shear test at the interface, it is possible to determine the bond strength of the layers in shear and the deformation. Based on the

FIGURE 18. Edge detection from the frames of the test video recording.

set of measured strength and deformation values, it is possible to define a stress-strain diagram (or load-deformation diagram) for multilayer walls, which can be implemented into software for more complex local analyses or global analyses of entire structures. The test performed is appropriate because the sample is mainly subjected to shear stress, and the samples represent structures of a three-layer monolithic-precast wall.

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REFERENCES

[1] A. D. Espeche, J. León. Estimation of bond strength envelopes for old-to-new concrete interfaces based on a cylinder splitting test. *Construction and Building Materials* **25**(3):1222–1235, 2011. https://doi.org/10.1016/j.conbuildmat.2010.09.032

[2] X. Hui-cai, L. Geng-ying, X. Guang-jing. Microstructure model of the interfacial zone between fresh and old concrete. *Journal of Wuhan University of Technology – Materials Science Edition* **17**(4):64–68, 2002. https://doi.org/10.1007/BF02838421

[3] P. K. Mehta, P. J. M. Monteiro. *Concrete: Microstructure, Properties, and Materials*. McGraw-Hill Education, New York, 4th edn., 2014.

[4] R. Hela. Příměsi do betonu [In Czech; Admixtures for concrete]. *BETON TKS: Technologie a materiály* (2):4–10, 2015. https://www.ebeton.cz/wp-content/uploads/2015-2-04.pdf

[5] J. Silfwerbrand. Shear bond strength in repaired concrete structures. *Materials and Structures* **36**(6):419–424, 2003. https://doi.org/10.1007/BF02481068

[6] E. N. B. S. Júlio, F. A. B. Branco, V. D. Silva. Concrete-to-concrete bond strength. Influence of the roughness of the substrate surface. *Construction and Building Materials* **18**(9):675–681, 2004. https://doi.org/10.1016/j.conbuildmat.2004.04.023

[7] Zkoušení ztvrdlého betonu – Část 6: Pevnost v příčném tahu zkušebních těles [In Czech; Testing hardened concrete – Part 6: Tensile splitting strength of test specimens]. Standard, Czech Standard Institute, Prague, 2001.

[8] Výrobky a systémy pro ochranu a opravu betonových konstrukcí – Zkušební metody – Stanovení pevnosti v šikmém smyku [In Czech; Products and systems for the protection and repair of concrete structures – Test methods – Determination of slant shear strength]. Standard, Czech Standard Institute, Prague, 2000.

[9] X. Wu, X. Zhang. Investigation of short-term interfacial bond behavior between existing concrete and precast ultra-high performance concrete layer. *Jianzhu Jiegou Xuebao/Journal of Building Structures* **39**:156–163, 2018. https://doi.org/10.14006/j.jzjgxb.2018.10.018

[10] K. M. Pufal, G. Savaris, S. L. G. Garcia. Evaluation of direct shear strength of self-consolidating and conventional concretes. *Revista Materia* **26**(3):1–10, 2021. https://doi.org/10.1590/S1517-707620210003.13036