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Quantification of Concrete-Concrete Interface Strength – A Review

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Abstract

The construction industry is experiencing a significant increase in hybrid concrete structures due to the need for repairing/strengthening of existing structures and the development of novel hybrid structures. The crack development and the ultimate capacity of hybrid concrete structures may significantly be governed by the properties of interface between the two concretes, making the quantification of interface properties essential. A large number of bond tests have been reported in literature but most of them do not result in a failure directly/entirely at the interface (unless the interface is very weak), resulting in only a lower bound estimate of the interfacial strength. Furthermore, the reported interfacial properties are only determined from small-scale bond tests where structural effects (like shrinkage) are limitedly taken into account. In the current study, the most commonly used bond tests are critically assessed in terms of the stress distribution caused by their inherent boundary conditions. Furthermore a testing procedure is then discussed which can allow for the quantification of the interfacial properties. A possible structural test is also designed which forces the failure to localize at the interface and allows to determine interface properties considering structural effects.

1 Introduction

In recent decades, the construction industry has seen a significant increase in the types of novel concretes like Strain Hardening Cementitious Composites (SHCC) and Ultra High Performance Fiber Reinforced Concrete (UHPFRC). These concretes are attractive for application in construction industry due to their superior ductility and higher tensile and compressive strength when compared to conventional concrete. However, these fiber-reinforced concretes are more expensive compared to conventional concrete due to the fibers incorporated in the cement matrix and finer particle packing (consisting of more binder and finer grades of sand/aggregates). An optimal solution is to use these expensive concretes only in the critical locations of the structures – e.g. the zone/area with high tensile stresses. Ageing and deteriorating reinforced concrete structures also demand repair and maintenance. Some structures might need to be strengthened to sustain increased design loads (like the increasing traffic loads). In such cases, existing reinforced concrete structures are repaired/strengthened by adding a new layer of concrete on top of the existing concrete. In all such applications (new hybrid constructions or repair/strengthening of existing infrastructures), the combined response of the hybrid structural member might be significantly influenced by the properties of the interface under service and ultimate loads. Therefore, an appropriate estimation of the interface bond strength is essential for successful design of hybrid structures.

Current design codes provide limited information on the quantification of the interfacial strength between the two concretes, mostly relying on ensuring a minimum roughness of the interface or a minimum tensile strength. For example, fib model code [1] categorizes interface based on peak-to-mean roughness (R_t) as very smooth (immeasurable R_t), smooth ($R_t < 1.5$ mm), rough ($R_t \geq 1.5$ mm) and very rough ($R_t \geq 3$ mm) while the Eurocode [2] distinguishes between the strength of very smooth (cast against steel/wood), smooth (slip-formed or free surface), rough (3 mm roughness with 40 mm spacing) and indented (5 mm roughness with less than 50 mm spacing) interfaces. Such classifications are quite broad; hence the suggested strength parameters are extremely conservative. A more detailed approach to analyze hybrid structures can be to simulate the behaviour of concrete-concrete interface using finite element or discrete element models. However, due to lack of experimental information on the behaviour of concrete-concrete interface under combined loading (like tension and shear), such efforts also involve conservative assumptions or calibration of interface properties [2],[3].

There are several bond strength tests suggested in the literature [4]–[6], also discussed later in the paper, to determine the strength of the interface. Most of these tests cause different stress-state at the interface due to their inherent boundary conditions, thus resulting in a different measured bond strength. Currently there is no consensus on the most suitable bond test and the testing procedure is recommended to be selected based on the expected stress-state of the interface in the real structure – making the choice subjective and user dependent.

This paper briefly discusses the factors affecting interface behaviour, critically reviews the existing bond strength tests in terms of the boundary conditions and the stress-state at the interface and proposes a multi-scale approach for quantification of interfacial properties.

2 Factors Affecting Interface Strength

Once the new (overlay) concrete is cast against the hardened existing (substrate) concrete, the interface starts to develop within the freshly cast overlay; therefore, the interface is also referred to as Overlay Transition Zone [8]. The strength of this interface depends on several parameters which are important to consider while designing the interface. The most important parameters and their influence on the bond strength are briefly discussed in this section.

The hardening overlay concrete forms a chemical and physical bond between the substrate and the overlay. Therefore, the chemical composition and mechanical strength of both the concretes affect the adhesion strength of the interface [7]. A direct correlation between the strength of overlay and the strength of interface has been reported in several studies [8]–[10]. The moisture condition of the substrate before the overlay is cast has also been studied by various researchers and varying accounts are found on the subject. Some authors report a saturated surface dry condition to result in the highest bond strength [12] while others report no effect of the moisture condition [8]. A distinction between the effect of moisture condition on the tensile and the shear strength of the interface is also reported where, a saturated surface dry condition results in higher tensile strength, while a dry substrate results in higher shear strength [13]. Substrate surface roughness is reported to be the most significant parameter affecting the interface strength and significant research has been reported on the subject [6],[10]. However, most of the authors (and codes) only refer to the average roughness of the interface which is highly criticized due to its inability to capture significant changes in the interface roughness profile [13]–[15]. Some aggressive procedure, like jackhammering, are also reported to induce micro cracks in the substrate concrete which are detrimental to the interface bond strength [16]. The dependence only on the mean roughness of the interface together with the use of such an aggressive technique could thus lead to inappropriate design of the interface. The curing condition of the composite also influences the effective strength of the interface since the interface can be pre-damaged due to the differential shrinkage of the two concretes [16]–[18]. This effect might be even more critical for novel materials which have larger shrinkage than conventional concrete. Furthermore, the shrinkage effects are more pronounced in actual structures than in the bond test. The bond tests alone do not provide the necessary conditions to study the effect of differential shrinkage, which is also a size dependent phenomena. The use of bonding agent at the interface before casting the overlay concrete also significantly influences the interface bond strength [20]. This results in more than one interface to develop and thus is even more complex to investigate. In some applications, steel reinforcement crossing the interface is also applied which increases the shear transfer ability of the interface due to the dowel action of the rebar [21]. In practice, most of the interfaces are reinforced due to their brittleness, as well as lack of knowledge and confidence in unreinforced concrete-concrete interfaces.

3 Bond Strength Tests

Several bond strength tests have been reported in literature [4]–[6] which can be used to quantify the tensile, shear, tensile-shear or compression-shear strength of the interface. The tests can be broadly divided in direct and indirect tests. The aim of the direct tests is to produce a homogenous stress state at the interface either in shear or in tension. The indirect test methods assume/calculate the stress distribution at the interface and use analytical expressions or inverse analyses to derive the bond strength.

It is important to mention that for appropriate quantification of the interfacial bond parameters, the bond test should result in a failure directly and entirely at the interface, otherwise only a lower bound estimate of the bond strength is obtained. The interfacial properties are also reported to be size-dependent so the same geometry of the specimen is essential when comparing the results under varying stress-states or when studying the effect of the parameters discussed in Section 2, including the rebar crossing the interface. To simulate the interface, the tension-softening and the shear-slip response of the interface is essential; hence the bond test should also be stable after the peak load. Although the influence of differential shrinkage in bond tests is limited, it can damage or pre-load the interface which should be avoided. Thus, an ideal bond test would:

- enable the failure to be directly and entirely at the interface;
- allow to develop compression-shear and tension-shear stresses on the same specimen geometry;
- allow to capture post-peak response of the interface in tension, shear and combined loading;
- have limited influence from structural phenomena like shrinkage;
- allow to measure the strength of reinforced interfaces.

The most commonly used testing procedures are critically assessed in this paper with a distinction between tensile, shear and combined tests (interface loaded perpendicular and parallel to its plane).

3.1 Tensile Bond Tests

The most popular tensile bond strength tests are schematically drawn in Fig. 1. The direct tension tests are characterized by an applied load perpendicular to the interface while the indirect tension tests have the applied load parallel to the interface.

Due to its simplicity and the possibility for in-situ testing, the most widely used tensile test is the pull-off test (a in Fig. 1) [21]–[23]. During testing, a core is drilled at least 10 mm [23] (preferably 25 mm or half the diameter of the drilled core [22]) below the interface position and a tensile force is then applied on the drilled core. The major advantage of the test consists in the possibility of in-situ testing, where the interface is tested in real situation, and ease of application. Although it is easy to perform and has been adopted as one of the standard tests for the interfacial tensile strength, the test shows a large scatter in results because even small eccentricities in loading induce bending stresses at the interface. Furthermore, the damage caused during the drilling operation and the depth of the drilling also influences the obtained results [22] and the failure is rarely at the interface. A more uniform tensile stress can be developed at the interface using the direct tension test [25] (b in Fig. 1). This test is also susceptible to the errors caused by eccentric loading, but these are generally well-controlled in stiff laboratory setups with no hinges when compared to pull-off tests. Nonetheless, even for this test the failure is not always at the interface giving only a lower bound interfacial tensile strength [26].

All the indirect tension tests (c-e in Fig. 1) apply the load parallel to the interface and are adopted from the splitting test of monolithic concrete [27]. In all such tests the stress distribution is not uniform at the interface but the results have less scatter compared to direct methods due to relatively well-controlled boundary conditions. These tests can also be used to capture the post-peak behavior of the interface which can be used for quantification of fracture energy [28]–[31], necessary for simulating the interface. However, these tests are hard to use with rough interface profiles due to high local stress concentrations and they only allow the quantification of the interface strength under tensile loads.

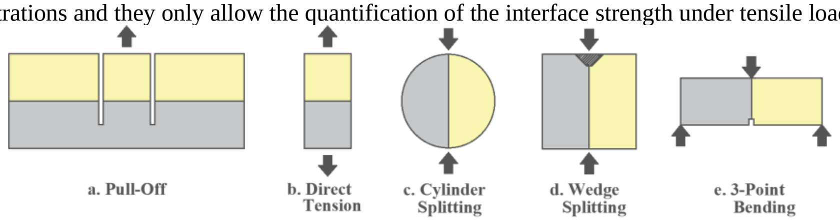

Fig. 1 Most popular direct and indirect tensile bond tests for concrete-concrete interface.

3.2 Shear Bond Tests

The most commonly used bond tests for direct estimation of the interfacial shear strength assuming a theoretically pure shear loading on the interface are shown in Fig. 2. The major limitation of almost all the direct shear tests is the existence of bending moment at the interface during loading: this makes it difficult to have a direct measure of the shear strength. Still, for most of the direct shear tests, an assumption of pure shear at the interface is commonly made to calculate the interface shear strength.

The torsional shear test (a in Fig. 2) is similar to the pull-off tension test but instead of loading the drilled core in tension, a torque is applied. This method was suggested by Silfwerbrand [32] to measure the in-situ shear strength of concrete-concrete interfaces. However, this method rarely results in an interface failure thus only a lower bound estimate of the interface shear strength can be obtained. The push-through and double guillotine (b and g in Fig. 2) are designed so that there is theoretically pure shear at the interface due to symmetric loading but due to the presence of two interfaces, the behaviour of one interface is dependent on the fracture/performance of the other. This condition is even more complex to analyze, making the test impractical. The direct shear test (c in Fig. 2) represents the most simple approach to load the interface in shear but due to the eccentricity between the two loads, a bending moment is applied on the interface leading to premature failure and underestimation of the interface shear strength. The bi-surface shear test [33] (d is Fig. 2) has also been a popular choice because it is easy to cast and test in the laboratory and causes predominantly shear stresses at the interface. However, after the attainment of the peak strength the tests becomes unstable. The Guillotine tests (e, f and g in Fig. 2) load the interface predominantly with shear stresses but they are hard to control in the laboratory due to complex adjustment of the forces. Furthermore, after the initiation of failure they become unstable due to the loading scheme and self-weight of the specimen and do not allow to capture the post-peak response. Among direct shear tests, the push-off test has been most extensively used due to limited influence of bending moment and direct computation of the shear strength. Although casting is somewhat challenging, the testing method has been widely used with [34]–[36] and without [37] reinforcement in the L-shapes of substrate and overlay concretes. A new shear strength test is also suggested in efforts to capture the post-peak behaviour of the interface under shear loads [38] (i in Fig. 2). This tests can be used with tensile or compressive loads and can results in a relatively stable interface failure, but due to the presence of four interfaces in the sample, it represents a complex system.

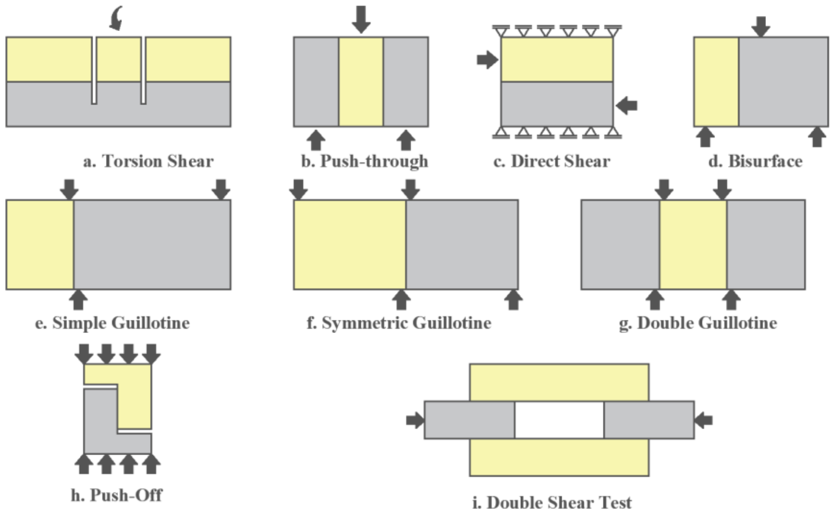

Fig. 2 Shear bond tests without normal stresses for concrete-concrete interface.

3.3 Combined Shear and Normal Stress Tests

Along with the tests that aim at producing pure tension or pure shear at the interface, some tests (shown in Fig. 3) are designed to cause combined normal and shear stresses at the interface to represent more realistic loading situations. The direct compression shear test (a in Fig. 3) is easy to perform in the laboratory and can be used to quantify the shear strength of the interface for varying normal stresses. However, the eccentricity between the loads makes this test suffer from the same limitations as the direct shear test. The most popular among the combined test is the slant shear test (b and c in Fig. 3) which is adopted from the test of epoxy-resins on concrete [39]. The suggested specimen in the standard [39] has a cylindrical shape and an angle of 60° with the horizontal plane. This geometry is reported to suffer from the chipping failure at the sharp corners in substrate and overlay around the interface leading to large scatter in experimental data. Furthermore, due to the fixed angle of the interface, only one combination of shear-normal stresses is obtained. This stress-state allows the failure to localize at weak interfaces, but for stronger interfaces a mixed or cohesive failure has been reported. Over the years, several modifications to this geometry have been suggested to reduce the scatter in the results and to ensure the failure at the interface, including casting of prisms [11], reinforcing the substrate and overlay [40] and varying the angle of the interface [28],[41],[42]. The slant shear test is generally performed under compression causing compression-shear at the interface and due to the high strength under this combination of stresses, the test becomes unstable after peak load.

Although limited, tensile slant shear tests are also reported in literature [28],[42] for varying angle of the interface with some modifications to the geometry, as discussed later in the paper. For all the bond tests, it is normally assumed that the effects of differential shrinkage can be ignored due to the small size of the specimen, but an inverse correlation between the total free shrinkage and the slant shear strength of the interface is also reported [19]. Furthermore, the stress distribution at the interface is non-uniform due to the difference in the moduli of the two concretes [43]. Recently, a double-edge notch test (d in Fig. 3) has also been suggested for the shear strength quantification of the concrete-concrete interface [44]. The authors used Digital Image Correlation (DIC) and finite element modelling to verify that the interface failed predominantly in shear due to the boundary conditions of the new testing method. However, due to the indirect loading of the interface, such tests would always be influenced by the stresses caused by the restrained deformation of one of the two concretes making the results harder to analyses.

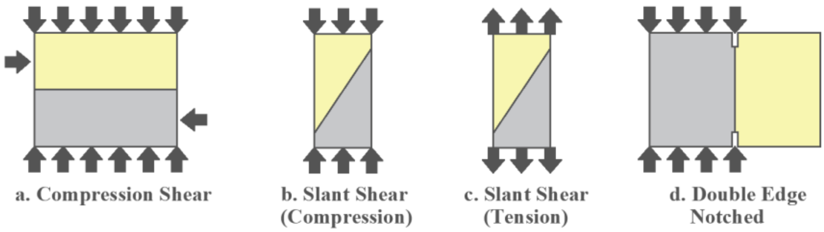

Fig. 3 Combined test with shear and normal stresses at the interface.

4 Proposed Multi-scale Approach with Modified Bond and Structural Test for Interface Characterization

Given the varying response of the interface under different stress conditions and the limited influence of shrinkage in bond tests, a multi-scale approach with varying stress-state at the interface is proposed for proper characterization of interfacial response. Wagner [29] suggested casting and testing modifications to the slant shear specimen. Although difficult to control in the lab, the modified tests fulfill almost all the requirements for an ideal interface bond test. The testing procedure includes casting slant shear specimens with varying angles of the interface as shown in Fig. 4, where the angle of 0° represents a direct tension test and the angle of 90° represents the push-off test. The presence of notches in the test with 0° reduces the area of the bonded region encouraging an interfacial failure. Similarly, the notches in the samples with varying angles can be adjusted such that the interface experiences the highest stresses while keeping the total area of the interface same in all the tests, avoiding any influence of the size effect. The notches in the specimen are made using a saw after hardening of the overlay concrete and just before testing. This not only protects the interface from the wall effects but also relieve the region of interest from the stresses caused by differential shrinkage, which are highest at the edges. These specimens can be tested in both compression and tension allowing a compression-shear and tension-shear test on the same geometry. However, compression test on the samples with an angle of less than 60° would most probably exhibit a cohesive failure governed by the crushing of the weaker concrete, and thus is trivial to perform. The push-off type specimen (angle of 90°) can also be fitted with reinforcement crossing the interface to investigate the dowel action.

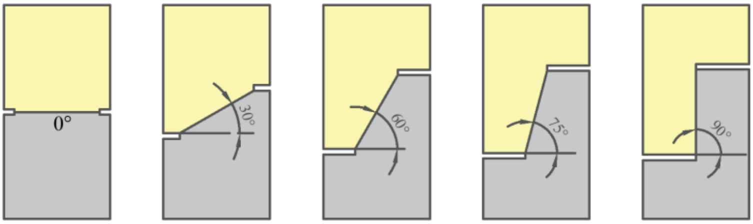

Fig. 4 Modified slant-shear test with varying interface angle.

The specimens shown in Fig. 4 can be used to capture the post-peak behavior of the interface when tested in tension. Fig. 5 (left) and 5 (centre) show one of the samples tested by Wagner along with load opening response of the samples with 75° and 90° of angle. The results show variations between the top and bottom notch, signifying the non-uniformity of stresses at the interface. Therefore, this non-uniformity of stresses has to be taken into account while performing the inverse analysis to determine the tension-softening and shear-slip response of the interface. However, since interface opening and interface slip were measured only at two positions (around upper notch and lower notch) using two sets of Linear Variable Differential Transformers (LVDTs), conclusive results could not be obtained in the study [29]. Using a photogrammetric technique like DIC would provide a better opportunity for a successful inverse analysis since it captures the full-field deformations of the sample. Therefore, an experimental series on modified slant-shear tests with DIC is currently being conducted by the authors. The principal strain field for a specimen with an angle of 75° and the corresponding interface slip obtained from DIC are shown in Fig. 5 (right). The interface slip is calculated using the open source code for Automated Crack Detection and Measurement (ACDM) [45].

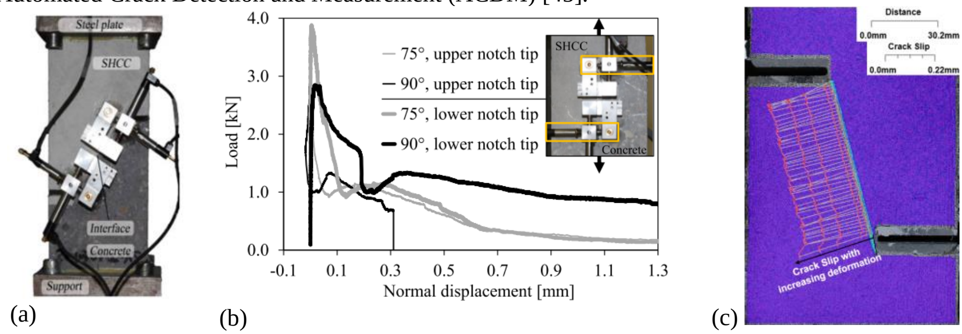

Fig. 5 (left) Testing and measurement procedure used by Wagner. (centre) Results of 75° and 90° angle of the interface from [28] and (right) DIC results of a 75° specimen showing interface slip with increasing deformation.

The properties of the interface are also reported to be size-dependent [11] and there is limited evidence to support that the properties of interface determined from the bond tests can directly be used for predicting the behavior of interface in structures. In efforts to fill this knowledge gap, a structural test that encourages the failure to localize at the interface is shown in Fig. 6 [46]. The boundary and loading conditions of the suggested structural test enables that the environmental and mechanical loading cause maximum stresses at the same location (at the central notch), encouraging the failure to localize at the interface and allowing to study the damage caused by shrinkage. These structural tests are also being conducted by the authors in line with the suggested multi-scale approach to characterize the interface.

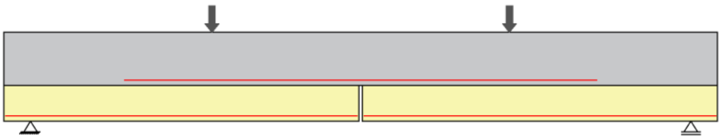

Fig. 6 Structural test for investigating the interface strength including the effect of differential deformations of the two concretes.

To determine the interfacial model parameters for the design/analysis of hybrid structures, an approach based on combined bond and structural tests should be used, where both the tests encourage the failure to localize at the interface.

5 Conclusions

Appropriate quantification of the interfacial model parameters is essential for design of hybrid structures. Several bond tests are available for testing the interface in tension, shear and combined loading. However, the results vary significantly from one test to another due to different stress states at the interface caused by the inherent boundary conditions of the bond tests. Currently, there is no consensus on the most suitable test method and varying opinions are found in literature. An ideal bond test would allow the failure to localize directly/entirely at the interface and allow to study the effect of varying the combination of stresses (tension-shear and compression-shear) at the interface while being stable after the peak strength so the post-peak response can also be captured. In addition, due to size effect and the differential shrinkage between two concretes it is essential to quantify the role of shrinkage in tests for interfacial strength quantification. A multi-scale approach using a series of modified slant-shear test coupled with a structural test using full-field measurement is discussed to be promising in getting a deeper insight into the interfacial model parameters.

Acknowledgements

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