Design of shear transfer in concrete-concrete composite structures

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Summary

For the design of concrete composite constructions, the transfer of internal stresses across the bond interface between new and old concrete is a critical aspect. A design method has been developed with the aid of specific tests for rough, sand-blasted and smooth surfaces. Test results known from literature have been taken into account. This new design approach considers cohesion, friction and the shear resistance of the reinforcement in determining the effective shear transfer. It has been found that, contrary to the usual design approach, the full yield strength of the reinforcement cannot be equated to the tension clamping force across the interface.

1. Introduction

Placing new concrete on older concrete is a routine task in construction. It occurs at every joint in concrete construction work. For some time now, placing overlays has gained in importance as a result of the more frequent strengthening of existing structures. In such cases, a loadbearing layer of new concrete (overlay), is placed on the existing concrete structure. This overlay is usually cast directly or placed as shotcrete. It functions to augment the flexural compression or flexural tension zones, depending on the placement.

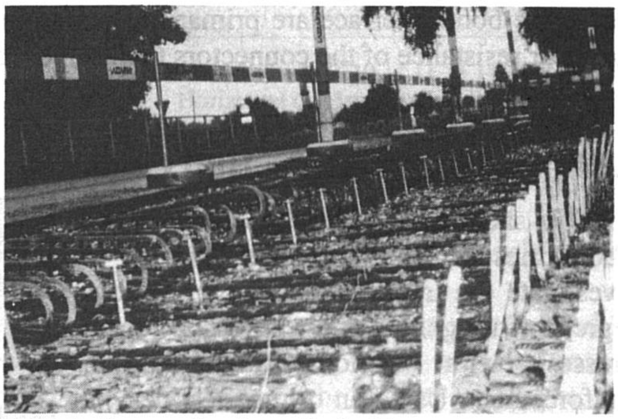


Fig. 1: Strengthening of a bridge

One of the problems encountered is the transfer of internal stresses acting across the bond interface between the old and the new concrete. In this respect, knowledge is required of the resistance of the bond interface to tensile and compressive forces in any direction. Initially, stresses in the bond interface result from a combination of external loads and internal forces of constraint. It must be borne in mind that stresses due to shrinkage and temperature gradients in the new concrete typically reach their maximum at the perimeter of the overlay. The combination of external and internal stresses often exceeds the capacity of the initial bond, thus requiring the designer to allow for a debonded interface. This is particularly true in the case of bridge overlays which are subject to fatigue stresses resulting from traffic loads. Furthermore, these stresses are dependent on time, and bond failure can take place years after overlay placement.

2. State of the Art

Review of the literature reveals little research into the specific behavior of reinforced bond interfaces between new and old concrete. The majority of the existing studies concentrate on the transfer of shear forces across cracks [6].

The effect on the shear loading capacity of subsequent roughening the surface of the old concrete was first investigated in 1960 in the United States. A few years later, the so-called shear-friction theory was developed. This theory attempts to explain the phenomena with the aid of a simple saw-tooth model. According to this, the roughness of surfaces in the case of relative displacement always leads to a widening of the interface which sets up stresses in steel connectors passing across the interface. They, in turn, create clamping forces across the interface and thus also frictional forces. In the middle of the 1970's, further shear tests were conducted in New Zealand (Paulay [4]), in the United States (Mattock [5]) and in Germany (Daschner [7]).

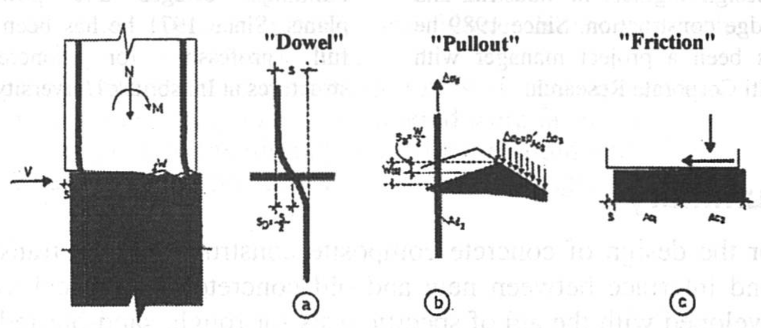


Fig. 2 Shear transfer in cracked concrete [8]

In 1987, Tsoukantas and Tassios [8] presented analytical investigations into the shear resistance of connections between precast concrete components. They cover the different contributing mechanisms of friction and dowel action (fig. 2).

In 1991/92, Menn [9], in Switzerland, looked into the behaviour of bond between old and new concrete using a series of beams which had been strengthened by additional reinforcement in a new layer of concrete placed on the underside of the beams.

The results clearly demonstrated that a significant increase in loadbearing capacity can be achieved by proper roughening of the surfaces. If the surfaces are very rough, the steel connectors across the bond interface are primarily stressed in tension, whereas, if the surfaces are smooth, the shear resistance of the connectors themselves (dowel action) predominates.

3. Laboratory Tests by Hilti Corporate Research

Specific shear tests were carried out in the laboratories of Hilti corporate research to investigate the interrelationships of various degrees of roughness and transferable shear stresses with various amounts of reinforcement. Using an origine test design, it was possible to avoid any eccentric moments in the specimen and to allow for parallel separation of the interface surfaces (fig. 3). The roughened surfaces were treated with a de-bonding agent before the new concrete was placed.

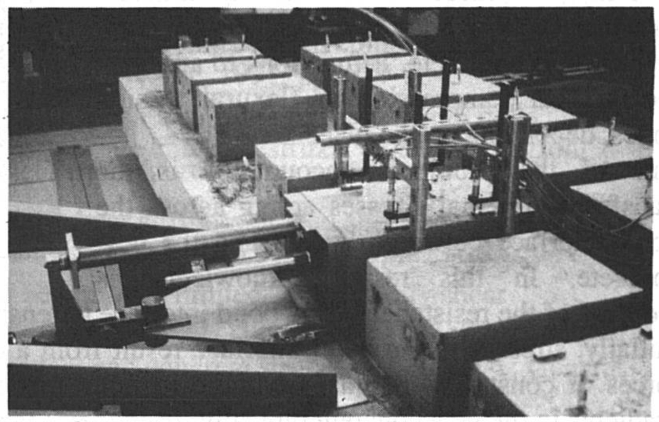


Fig. 3: Testing arrangement

The test results confirm the strong influence of roughness on shear resistance and shear stiffness. If the load-displacement curves are regarded in conjunction with the measured displacement, the three components of cohesion, friction and dowel action can be isolated and determined quantitatively. They make different contributions to the overall resistance (figs. 4, 5 and 6), depending on surface roughness and amount of reinforcement.

Hence, the frictional component predominates when the surface is blasted with a high-pressure water jet and larger amounts of reinforcement are provided. But small shear stresses can also be transferred even when no reinforcement is present, due to the good interlocking effect of the interface surfaces. In the case of sand-blasted surfaces, however, shear stresses are transferred by a combination of friction and dowel action, but the forces that can be resisted are generally far smaller than in the case of high-pressure water blasting.

It was also investigated whether the post installed rebar connectors are stressed to yield at ultimate shear transfer. For this purpose, the strain in the connectors at the level of the interface was measured. To avoid any disturbance of the bond, and in order to obtain the strain from tensile loading only, strain gauges were fixed in a central bore in the axis of the connectors.

These test results clearly show that, when surfaces have the above-mentioned degrees of roughness, the tensile force in the connectors does not reach the full tensile yield strength, contrary to assumptions for current design models. Tests carried out with connectors of various lengths confirm this result as they showed that reduced anchorage lengths are sufficient to carry the effective connector tensile force at maximum shear transfer capacity. Additional connector embedment (e. g., as required for theoretical connector tensile yield) did not result in increased shear transfer.

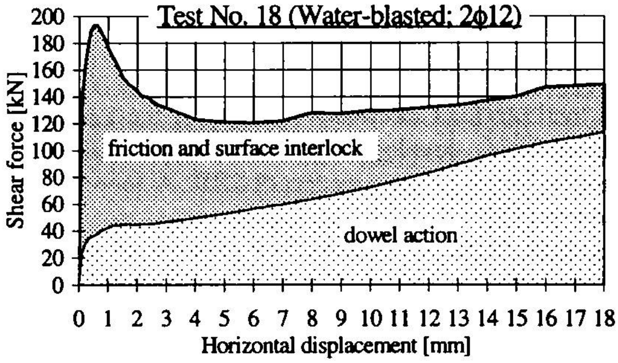


Fig. 4: Water-blasted surface

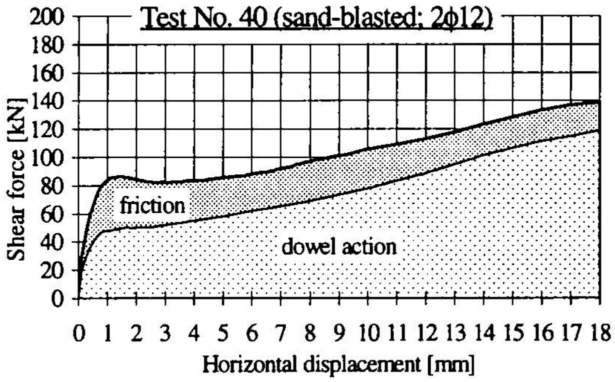


Fig. 5: Sand-blasted surface

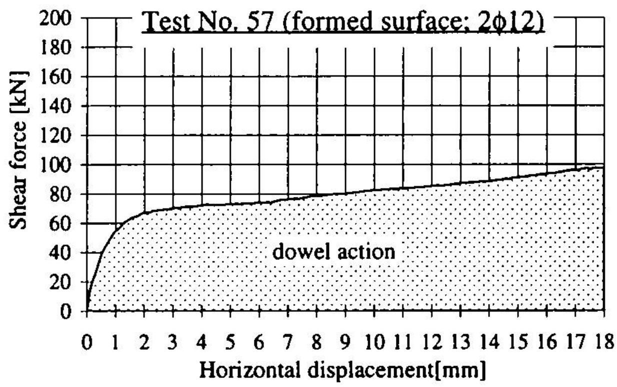


Fig. 6: Smooth surfaces

The loadbearing behaviour of smooth interface surfaces with connectors was also investigated. As displacement readings for the horizontal and vertical directions showed, there is in this case also a separation of the interface under shear loading and, thus, owing to the lack of roughness, a loss of contact between the shear surfaces. In this case, the entire resistance comes from dowel action.

On the basis of these findings, design approaches can now be developed which permit separate and realistic analyses of the various components of shear resistance. As a result, a standardised level of safety is ensured with respect to resistance, no matter whether the normal stresses at the interface are set up by an external normal force or internal connectors.

4. Design of Shear Transfer

4.1 Miscellaneous

The Institute for Concrete Structures of the University of Innsbruck, Austria, provided scientific support during development of this design method, which is based on EC2 [1]. The evaluation is contained in the thesis by Randl [10]. A more comprehensive description and examples can be found in [13].

Structures made of reinforced or prestressed concrete, which have a concrete overlay of at least 60 mm, may be designed as a monolithic building component if the shear forces acting in the interface between the new and the old concrete are resisted according to the following rules.

4.2. Loadbearing Capacity of Interface

Generally, an interface must be assumed to be cracked for design work. Connectors installed across the interface must be positioned in such a way that the shear force, V_{Rd}, between the new and the old concrete is transferred in the ultimate limit state.

$$V_{Rd} = \tau_{Rdj} \cdot b_j \cdot l_j \geq V_{Sd} \qquad (1)$$

V_{Rd} Design value of interface shear force resistance
V_{Sd} Design value of interface shear force due to actions
τ_{Rdj} Design value of the transferable interface shear stress in zone under review as per formula (2)
b_j Width of interface in zone under review
l_j Length of interface in zone under review

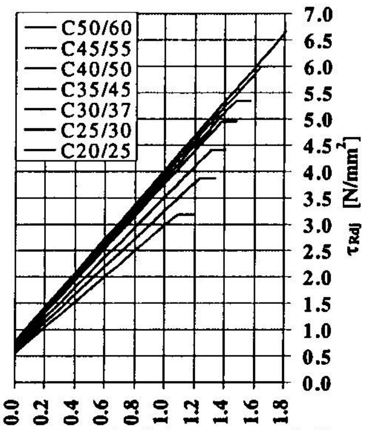
The design value of transferable shear stress, τ_{Rdj}, can be calculated using formula (2) [10]. When doing so, the upper limit is given by the transferable compressive stress in the strut model for concrete:

$$\tau_{Rdj} = k_T \cdot \tau_{Rd} + \mu \cdot (\rho \cdot \kappa \cdot f_{yd} + \sigma_n) + \alpha \cdot \rho \cdot \sqrt{f_{yd} \cdot f_{cd}} \quad \leq \quad \beta \cdot \nu \cdot f_{cd} \qquad (2)$$

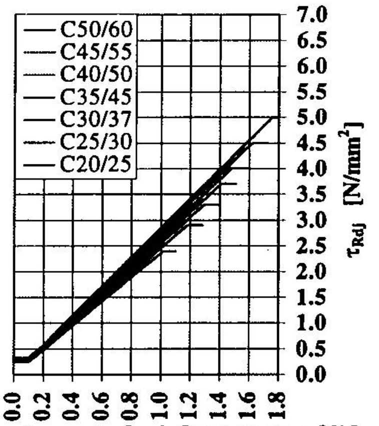
cohesion — friction — dowel action — compressive strut in concrete

τ_{Rd} basic value of design shear strength as per [1], section 4.3.2.3 (smaller value of new/old concrete)
k_T cohesion factor as per [13], table 1
μ coefficient of friction as per [13], table 1
α coefficient of dowel action as per [13], table 1
β coefficient as per [13], table 1
ν coefficient as per [1] formula (4.20)
κ coefficient for tensile force in the connector as per [13], table 1
$\rho = A_s / b_j l_j$ amount of reinforcement from connector in zone under review
$\sigma_n \leq 0{,}6\, f_{cd}$ normal stress to external loads acting on the interface (compression positive)
f_{yd} design value of yield strength of connectors
f_{cd} design value of cylinder compressive strength of concrete (smaller value of new and old concrete)
r mean roughness derived from sandpatching method (i.e. difference between peaks and valleys = 2r)

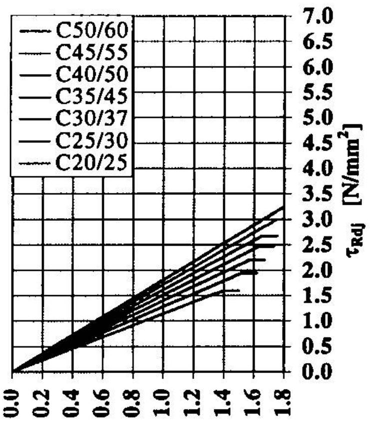
An evaluation of equations (1) and (3) for S500 grade steel is provided in the diagrams 1 to 3.



Dia 1: Water blasted surfaces



Dia 2: Sand-blasted surfaces



Dia 3: Smooth surfaces

4.3 Stressing of Interface

Normally, the design value of the interface shear force acting, V_{Sd}, is determined from the flexural resistance of the cross-section. Consequently, bending is decisive for failure of the cross-section and reference is made to full connection, as in steel-concrete composite designs [2].
In the perimeter of the concrete overlay, the crack tensile force, F_{cr}, of the concrete overlay must be transferred in accordance with [1], section 4.4.2.2. Particular attention must then be given to transfer of the moment from the crack tensile force in order to avoid spalling effects.

4.4 Serviceability Limit State and Design Principles

For normal cases, where water blasting is used, the stiffness can be determined, at the strengthened cross-section assuming full composite action. Where sand-blasted or smooth interfaces are used, a reduction of the stiffness must be expected.
Variations in surface preparation for the same building component should only be allowed if resulting stiffnesses along the interface variations are compatible from a displacement standpoint.
It must be noted here that interfaces with small shear stresses, without connectors according to section 4.3, may be assumed to be non-cracked for stiffness purposes.
The connectors must be adequately anchored in the old concrete and in the overlay. The actual tensile force, F_d, to be anchored may be taken as at least $F_d \geq 0.5 \cdot A_s \cdot f_{yd}$ when surfaces are rough or sand-blasted.
To shorten the anchorage length in concrete overlays, heads or plates can be provided. The concrete cone aswell as the bearing stresses in the concrete below the anchoring component must be checked. The methods of calculation are given in [14].
When surfaces are smooth, shear dowels must be anchored at depths of at least 6 times the diameter in each case, or, better still, to avoid dowel pull-out at large displacements a value of 9 times the diameter is recommended.

5. Comparison with Literature

In his thesis [10], Randl has proven through a study of literature and with reference to world-wide research results that the determined design equations are conservative. The results are shown in figs. 7 and 8.

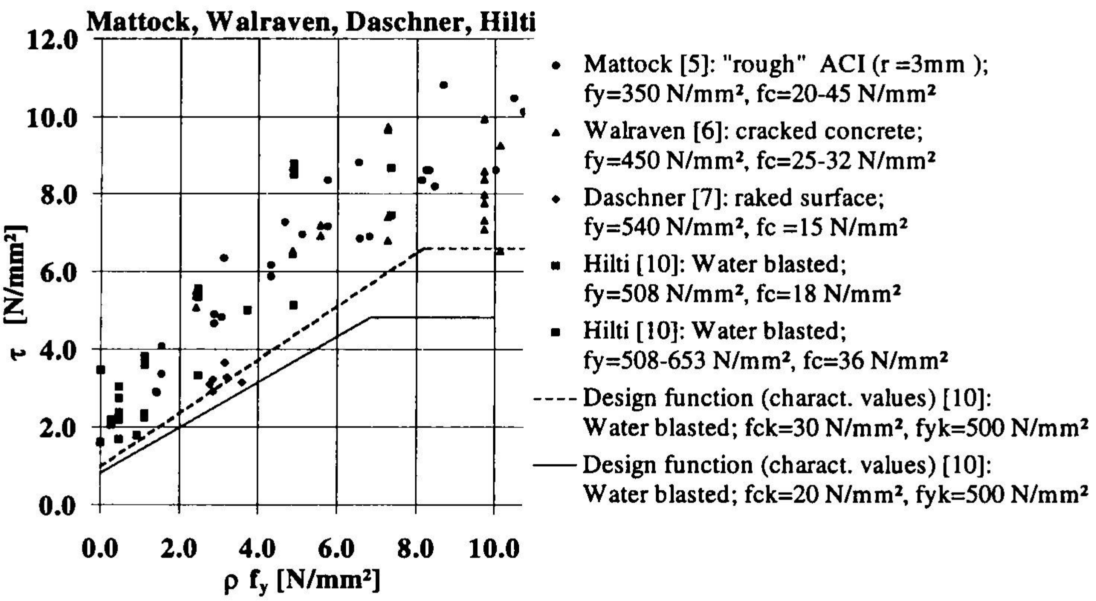


Fig. 7 Rough surfaces

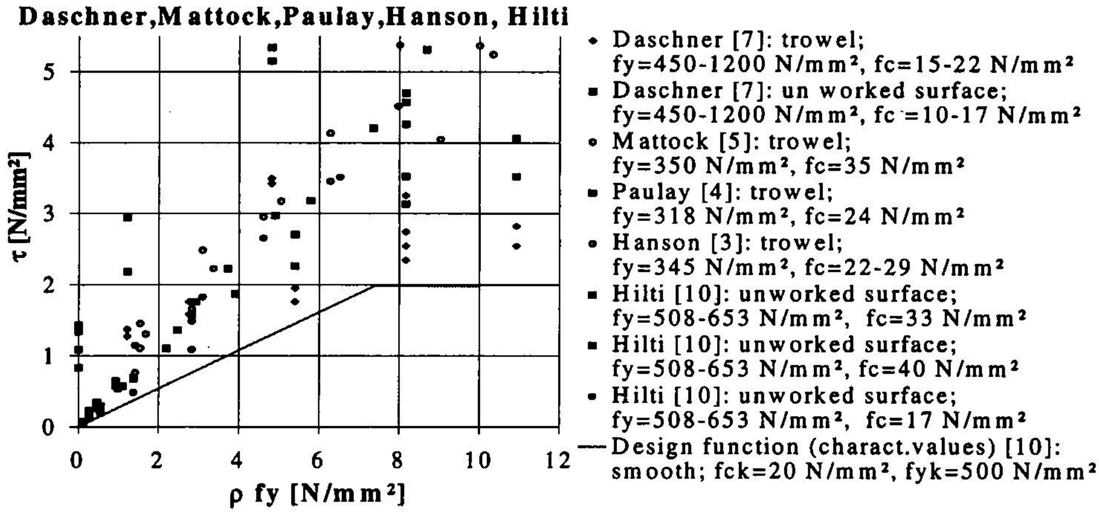


Fig. 8 Smooth surfaces

6. Summary

Contrary to design methods given in the literature, dowel resistance is considered along with cohesion and friction when determining shear resistance. With increasing roughness of surfaces, shear resistance and shear stiffness improve greatly. Furthermore, the distribution of total resistance shared by the three components changes considerably. The design method makes use of one single equation for calculating the resistance from the three components. In some cases, it is sufficient for the concrete overlay to be anchored at its perimeter.

This new design approach is particularly notable for its transparency. It is verified by the literature as well as by extensive testing conducted at Hilti Corporate Research. Through the use of design diagrams, the method can be made particularly straightforward for designers.

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