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ABOUT THE DEBONDING OF THIN CEMENT-BASED OVERLAYS

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Abstract

Cement-based overlays are used as repair, reinforcement, topping or lining of slabs, pavements and galleries' walls. Their debonding mechanism drastically differs from the one of bonded plates or strips reinforcing beams or slabs or of the layers of a laminated composite material. For the last group, bonding is ensured by organic glues which, typically, are weaker in shear than in tension. Consequently, their debonding is governed by the shear stress along interfaces. On the contrary, the cement-to-cement bond of cement-based overlays is characterised by a weaker strength in tension. Debonding is then governed by the tensile stress perpendicular to the base-overlay interface.

Different conditions of debonding of an overlay are reviewed. In all cases, the tensile stress perpendicular to the base-overlay interface is confirmed as the designing parameter. In terms of fracture mechanics, debonding of cement-based overlays is governed by a mixed mode in which mode I is widely dominating. There is a lack of appropriate tests to finely characterise the mechanical behaviour of the interface. Nevertheless, finite elements calculation relying on the mean values of the shear and tensile strength of the interfacial bond (we performed them with CESAR code) can provide a good approximation of debonding propagation.

Key words: overlays, debonding, repairs, toppings, linings

1. Introduction

Thin bonded overlays concern surface repairs, toppings and linings. They can be applied on slabs, slabs on grade (industrial soils), concrete pavements and galleries' walls. Their durability is dependent upon the one of their bond to the base structure.

It is widely considered that debonding occurs by shear along the base-overlay interface, Saucier (1990), Asad et al. (1997). Although shear is actual at the interface, it is always accompanied by tensions perpendicular to the interface and we shall show that these ones are generally decisive. Consequently, fracture mechanics of overlays debonding must not be limited to mode II. It must include mode I which dominates in the case of cement-based overlays.

After a brief comparison with laminated composite materials and with beam or slab reinforcements by bonded strips (made of metal or composite) we shall enlighten the specificity of thin cement-based overlays. Three different origins of their debonding will be investigated: the effects of the external loading of the structure, of a uniform length change of the overlay, of a non uniform length change of the overlay inducing curling. Actually, all these effects are superimposed, each of them being more or less influent depending on the case.

2. Comparison with laminated composites and with bonded plates or strips.

Bonded plates or strips are used to repair beams or slabs. Made of high tensile strength material, they carry high loads concentrated in small cross sections of reinforcement and are connected to the repaired structure through narrow strip like areas in which are induced high shear stresses. Ruin occurs by shear failure.

Peeling efforts at the tips of the reinforcing plates or strips are as well present, Varastehpour and Hamelin (1997a), Gay (1991), Bigwood and Grocombe (1989). As shown on Figure 1, they induce tensile forces perpendicular to the interface which act to debond. One notes that, for a given reinforcement capacity, the thicker the bonded reinforcement, the higher is the peeling moment and the more important are tensile stresses compared with the shear stresses.

In the case of bonded plates or strips, the reinforcement is thin and the peeling tensile stresses may remain of minor importance.

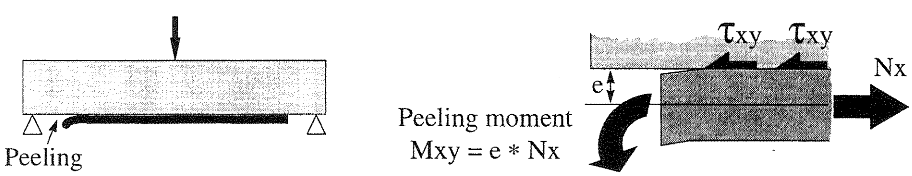


Fig. 1. Peeling at the tip of a bonded reinforcement

If necessary, the ends of the plates or strips are fastened by bolts or by a transverse bonded reinforcement, then peeling is prevented, Raoof and Zhang (1996), Varastehpour and Hamelin (1997b). The same phenomenon is encountered in laminated composites, as the laminae are very thin, it remains of minor importance.

On the contrary of bonded plates or strips, cement-based overlays have a low or medium tensile strength and may crack. They can carry large loads only because they are spread as a thick layer (compared with the thickness of bonded plates or strips) over the whole surface area of the reinforced structure. Consequently, the resultant stresses are of a lower level and a low tensile strength of the overlay associated with a poor or medium bond to the base can be satisfactorily efficient. Due to the higher thickness of the overlay, one can foresee a higher importance of the peeling tensile stresses.

There is an other fundamental difference between the laminated composites or bonded strips and cement-based overlays. It is the nature and the mechanical properties of the bond. In the first case, it is ensured by an organic adhesive characterised (whatever the breed of the glue), by a shear strength (maximum 12 MPa) twice weaker than its tensile strength (from 20 to 30 MPa), Gay (1991). On the contrary, in the case of the cement-to-cement bond of a cement-based overlay, sometimes enhanced by a latex-based admixture, its tensile strength (less than 2 MPa) is about two times weaker than its shear strength (until 6 MPa), Saucier (1990), Grandhaie (1993), Chausson (1997a).

Consequently, tensile stresses, comparatively with shear stresses, are four times more armful in the case of cement-based overlays. If the design of laminated composites is governed by shear stresses, in the opposite way the tensile stresses is the decisive parameter in the case of cement-based overlays.

3. Cement-based overlays: effect of external loading.

Two cases must be distinguished:

- debonding expected under a load applied on the overlay,
- debonding where the overlay is on the tensioned side of a bent structure.

3.1. Expectable debonding under a load applied on the overlay.

A study was carried out at the University of Sherbrooke (Canada), Do (1989), with the aim of causing debonding of the overlay by shear along the interface. It included static and fatigue tests which were performed in the conditions presented in Figure 2. The concrete base was reinforced by a metal plate to allow it to stand important loads. In a first run, a vertical load was applied (Figure 2a). With no previously debonded zone, debonding could never be achieved nor initiated, neither by static nor by fatigue loading (increasing the vertical load ended to the crushing of the compressed concrete of the overlay).

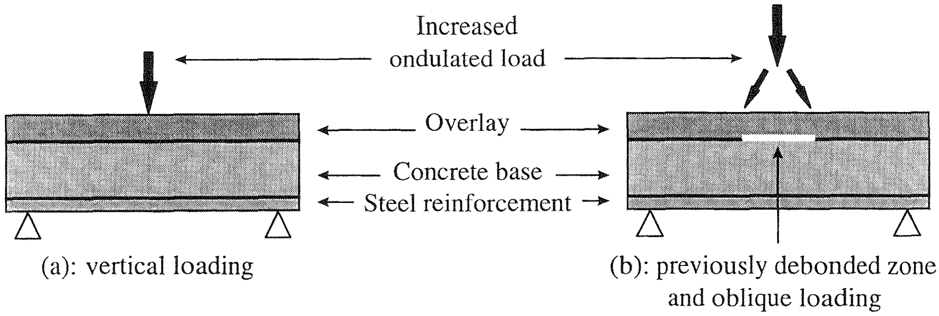


Fig. 2. Tests carried out in Sherbrooke , Do (1989), experimental device.

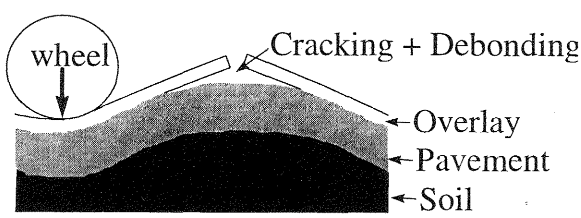
A second run was performed with an oblique load simulating the effect of braking (Figure 2b). It was still impossible to initiate debonding, but only possible to propagate a previously existing debonding.

From these results, it is obvious that debonding must not be expected under a load applied on the overlay. Indeed, in this area, although the shear stress is maximum, it is accompanied by the maximum compressive stress which acts to prevent debonding.

3.2. Debonding where the overlay is on the tensioned side of a bent structure.

In the case of pavements or slabs, such a case is met apart from the loads, in the zones of maximum negative moment. We demonstrated, Granju (1995), Granju (1996), Chausson (1997a), Chausson (1997b), that in these areas, if a crack or a joint cuts the overlay, debonding occurs according the mechanism presented in Figure 3. The cut through the overlay (crack or joint) makes debonding possible. Associated with the bending of the structure, it induces a high tensile stress perpendicular to the interface which, detrimentally, adds its effects to a peak of shear stress.

Among the different processes proposed to lead to debonding of thin cement-based overlays, only this one is able to give a good record of the enhanced durability of metal fibre reinforced overlays. Consequently it must be considered as a process of major importance.



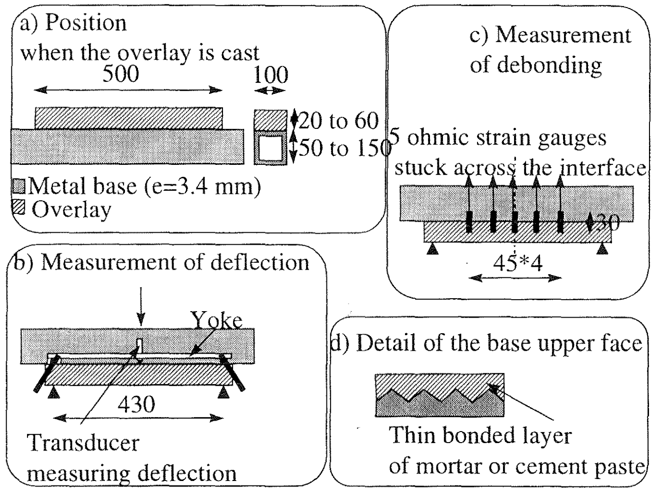


Fig. 4. Characteristics and testing of the composite specimens

Associating experiment and numerical modelling organised according to the factorial design technique, we carried out a thorough study of this mechanism.

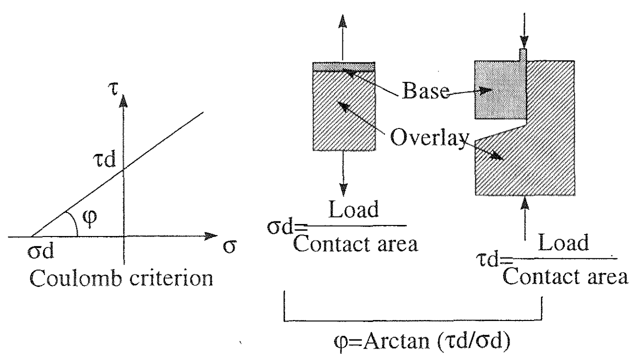
The experimental fold was performed as sketched in Figure 4. Composite specimens simulated repaired structures. Each of them was made of a bonded overlay cast onto a base. It was tested in flexure (mid-span load) with the overlay on the tensioned face. The true deflection, measured with a yoke, characterised the curvature imposed to the structure and it was increased at a constant rate. Debonding initiation and propagation were evidenced and monitored via five ohmic strain gauges stuck across the interface. The base was made of a hollow steel profile (100 mm wide and 3.4 mm thick). The nature of the base (metal or concrete) is not significant. The only important parameters are the curvature imposed to the interface, the mechanical characteristics of this interface and the relative thickness of the base and of the overlay. A metal base has the advantages not to be subjected to moister sensitive length changes as would be a concrete base, to be reusable and to have minimum mechanical discrepancy. The upper face of each base was milled rough and prepared by repeating the cycle - casting, curing and debonding a concrete overlay - until it was covered by a thin, uniform and perfectly adhesive layer of mortar or cement paste. So, the base-overlay interface is cement-to-cement type. Several thicknesses of the overlay and several heights of the base were considered, covering the range of 20 mm to 60 mm for the overlay and 50 mm to 150 mm for the base.

The numerical fold was performed with CESAR code developed by LCPC (Laboratoire Central des Ponts et Chaussées), France, for cement-based structures applications.

Two features of this code were particularly used: the probabilistic module and the contact elements. The probabilistic module was developed for structures made of cracking material, for instance concrete. Structures are modelled as clusters of volume finite elements stuck together by contact elements which have the tensile strength of the material. The elastic modulus of the volume elements and the tensile and shear strength of the contact elements are randomly distributed, according to a normal law, around their mean value. Here lays the probabilistic character of this code. Cracks initiate and propagate along the weakest paths encountered among the hazard of the randomly distributed strengths of the contact elements. The yielding of the contact elements is governed by their state of stress calculated at their mid-point. Consequently, their behaviour is more sensitive to the mean value of the stress rather than to the stress concentration at crack tip (at the extremity of elements). Regular contact elements were used to model the interface. As the previous ones, their yielding is governed by the stress at their mid-point.

This code was applied to model the experimental device. Once validated by comparison with the measured results, calculation was used to extrapolate experiments by varying the considered parameters in the factorial design process.

Among the basic parameters on which relies the model and among the factors which were varied in the factorial design process, there was the mechanical behaviour of the interfacial bond. According to Varastehpour and Hamelin (1996a), the interface was characterised by a Coulomb criterion. Its two basic parameters were measured by the tests presented in Figure 5, derived from those proposed by the previous authors. As indicated in Figure 5, σd and τd are mean values. They provide no record of the non uniformity of the stress field over the actual contact area in the test specimens. Nevertheless, with the contact elements described above, the best agreement with experiment was obtained when calculation was carried out on the base of these mean values.



In the case of metal bases, we measured $\sigma d = 0.5$ MPa and $\tau d = 1.3$ MPa from which we calculated $\varphi = 69$ °. These values correspond to a low or medium quality of actual work site base-overlay bond, Verhoeven (1990). In the case of concrete-over-concrete overlays, the highest values that we obtained in different other series of tests were $\sigma d = 2$ MPa and $\tau d = 6$ MPa. In conformity with literature, in both cases, τd was found larger than σd, the ratio $\sigma d/\tau d$ lays between 2 and 3.

From these results, in the factorial design process, σd was varied from 0 to 2 MPa and different values of the ratio $\sigma d/\tau d$ between 1 and 3 were investigated. The calculation showed that, in these limits, τd value has no effect, neither on debonding initiation, nor on its further propagation.

In conclusion, the tensile stresses perpendicular to the interface generated by this debonding mechanism and the weaker tensile strength of the bond add their effects so that the initiation and the propagation of debonding is governed by the tensile conditions along the interface. In terms of fracture mechanics one can say that, in the frame of this mechanism, even though a participation of mode II cannot be excluded in the propagation of debonding, mode I is widely dominating.

For fracture mechanics purpose, the tests used here, providing only the mean values σd and τd, are not convenient. They give no information about propagation and they ignore the stress concentration on the discontinuities. Peeling tests exist for composite materials and for bonded plates or strips. Unfortunately they do not work with brittle materials such as cement-based overlays. Convenient tests have to be developed.
Nevertheless, it is important to note that, when the behaviour of the contact elements is governed by their stress state at their mid-node, calculations relying on the mean values can provide a good prediction of crack propagation.

4. Effects of a uniform length change of the overlay

Length change of the overlay is due to shrinkage or to temperature. The limitation to a uniform length change is a simplification. In actual cases the intensity of shrinkage or of temperature changes varies with the depth inside the overlay. Such cases will be dealt with in the next point.

The uniform shrinkage of an overlay bonded to a concrete slab and the consecutive cracking and debonding of the overlay were modelled using CESAR probabilistic module. The shrinkage was simulated by a thermal contraction. The interface was modelled with the contact elements seen above and governed by the Coulomb criterion. Computation was carried out with two values of σd (1 or 2 MPa) and three values of τd (1, 2 or 3 MPa).

Once more, in the limits of this calculation, the results show no or insignificant incidence of the shear strength of the interface.

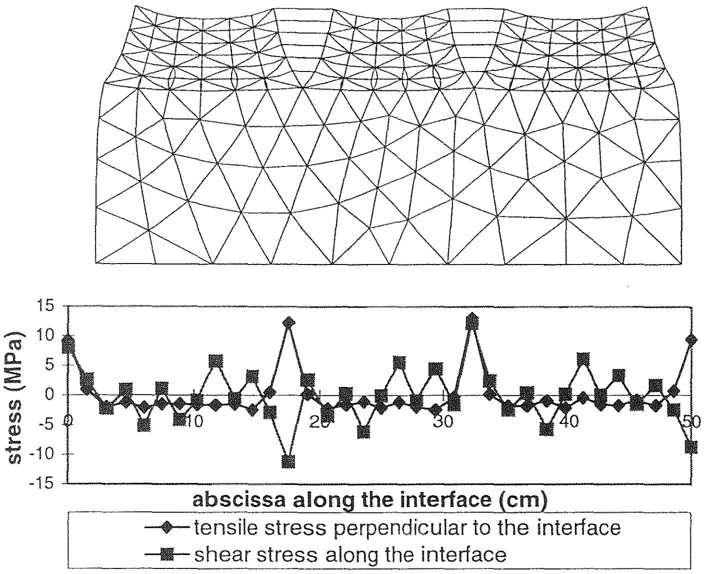


Fig. 6. Effect of a uniform shrinkage of the overlay: cracking of the overlay and stresses along the interface just before debonding initiation.

A typical result, extracted from the thesis work of H. Farhat, is presented in Figure 6, Granju (1998).

- The cracking of the overlay limits the level of stress and the number of cracks increases with the imposed shrinkage.
- The peak shear stresses are of the order of magnitude of the peak tensile stresses.
- Debonding at the edge of the specimen or from a crack is peeling type.

5. Effects of a non uniform length change of the overlay.

It is the case of actual overlays. A usual effect of non uniform shrinkage is debonding from the corners (at the edge of the structure or along the joints) with curling of the overlay. The stress state along the base-overlay interface is then the addition of :

- the effects of a uniform shrinkage of the overlay (seen above);
- tensile stresses perpendicular to the interface associated with restrained curling.

Consequently, the influence of the tensile strength of the base-overlay bond in the control of the initiation and the propagation of debonding is enhanced.

Calculation confirms this point and, still more than in the case of uniform shrinkage, varying τd has no or insignificant effect.

6. Conclusion.

On the contrary of the common belief, the design of thin bonded cement-based overlays must not focus on the shear stress at the base-overlay interface, but on the tensile stress perpendicular to the interface. The tensile debonding stress is the result of: first, the combined effects of bending of the structure and cracking of the overlay and second, the peeling force which is a consequence of the shear efforts along the interface.

In terms of fracture mechanics, mode I is widely dominating in the propagation of debonding, even if a participation of mode II cannot be excluded.

There is a lack of convenient tests to characterise the peeling behaviour of a cement-based overlay. Nevertheless, waiting for more appropriate measurements, the mean values of the shear and tensile strengths of the interfacial bond already allow us to calculate a good prediction of debonding propagation.

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