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Bonded cement-based overlays for the repair or the reinforcement of concrete structures

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1. Introduction

The ageing of concrete structures arises the problem of their repair.

Nowadays, as concrete has been used for more than half a century, many structures need repair at different degrees. Moreover, the number of new concrete constructions being in constant increase, repair works are promised to the same increase. Finally, the present concern of sustainable development, privileging repair instead of re-building, acts to the enhancement of the trend.

The thin bonded overlay technique is particularly suitable for the repair of large area structures. Of special interest are: slabs on grade (for instance industrial floors), pavements, bridge decks, walls and tunnels. Toppings and linings are also relevant of the same problematic. In the case of horizontal surfaces, the overlay is poured, else it is spread.

Usually, the bonded overlay technique applies to concrete parts having no structural failure. Then, the aim of the overlay may be either to smooth a damaged surface, to replace a distressed top layer or to improve the mechanical capacity of the structure by increasing its thickness, or a combination of these.

Millions of square meters in the world are already relevant to the bonded overlay technique.

Up to now, such repairs make problem because of their hazardous durability due to the hazardous durability of their bond with the substrate structure. Debonding starts from the ends, the joints and the cracks of the overlay, often with a lifting up of the edges of the debonded area. That induces new cracks which accelerate the damaging process and soon leads to the need of renewed repair works or of repair of the repair.

Nowadays, no reliable design is available for the practitioner. There are only numerous recommendations relying on experience and very crude design proposals.

The main concern in the field of bonded overlays is the bond between the overlay and the repaired structure, designated as "substrate". It is the prevalent factor, its durability is a synonym of durability of the repair system. Its quality of the bond results from the quality of the interface preparation and of the overlay placement process.

Debonding can result from chemical deterioration of the interface quality. Simple and well known precautions bring a good protection against such distress see Secs. 3.1 and 5.1.

More frequently, debonding results from physico-mechanical effects. Then, it is caused by the effects of the different length changes of the overlay and of the base, due to shrinkage or thermal changes, and by the effects of the mechanical straining of the repaired structure. In both cases, the same mechanism governs its initiation and propagation. A good control on the design goes through a thorough understanding of the bond and debonding mechanisms.

This Course proposes a survey of the main features and problems of the practice and durability of thin bonded overlays. In accordance with its qualification of "*advanced* course on design and application of *high performances* cement-based materials", the accent will be put on the recent developments of research in the field of the debonding mechanism understanding and modelling with a special insistence on the case of a high performance overlay system: the fibre reinforced overlay.

Two families of overlying works will be considered:

1. surface repair or strengthening of slabs on soil, pavements or floors,
2. surface repair or strengthening of bridge decks.

These two families have in common the concern of the necessary bond between the overlay and the substrate. In addition, the overlay can be designed and act as a protective layer against the ingress of aggressive agents. For both these functions, cracking is the enemy. They are different by the following points:

- Surface repairs or strengthening.
- It supposes that the overlaid structure has no or only minor cracks.
- Slabs (on soil or not), and concrete pavements repairs.

- In this case the overlay is at the same time the top layer and the wearing layer of the final structure. Consequently, it is exposed to weathering. That implies evaporation through its surface inducing high shrinkage with significant gradients through its thickness and significant length changes caused by the daily temperature changes. Moreover, it is directly exposed to the mechanical shocks caused by wheel crafts or falling objects. Finally, such overlays are usually rather thin, with a thickness on the order of 50 mm. If they are reinforced, only fibres are expected.
- Bridge decks repairs.
- The overlay is usually thicker, reaching often more than 100 mm in depth. At the same time, it often includes a reinforcement made with steel bars or welded steel fabric. The higher thickness of the overlay and its reinforcement with a conventional steel system provide a somehow different behaviour. Finally, in bridge decks the overlay is seldom the upper layer of the structure. It is generally covered by a wearing layer, often asphalt-based, which brings a protection against evaporation and against the direct injuries from the traffic. Then the shrinkage and temperature change strains are expected to be lower and more uniform along the depth of the overlay than in the case of slab repair or strengthening.

2. Problems of repair

The problems of repair of concrete structures in the most general case (ingress of external aggressive agents, corrosion of the steel reinforcements, etc.) are summed up in Fig. 1 from Emmons and Vaysburd [1]. This example wants to be the most general possible. It includes the protection function of repairs, notably the protection of the steel reinforcements against aggressive agents and corrosion. Nevertheless, the case illustrated in Fig. 1(a), a "patch repair" has its own restrictions. It differs from large area of bonded overlays, the object of this course, in two points. Because of the limited area of the patch layer, its shrinkage induced cracking can be expected to be of negligible or low extend. On the contrary, the great concern is then the debonding along the vertical peripheral face of the patch, which, for a matter of protection of the underlying structure, has the same detrimental effect as a crack, often of large opening.

The focus of this course is the large area of repair works, where the repair layer covers the whole area of the repaired structure. Patch repairs will not be considered.

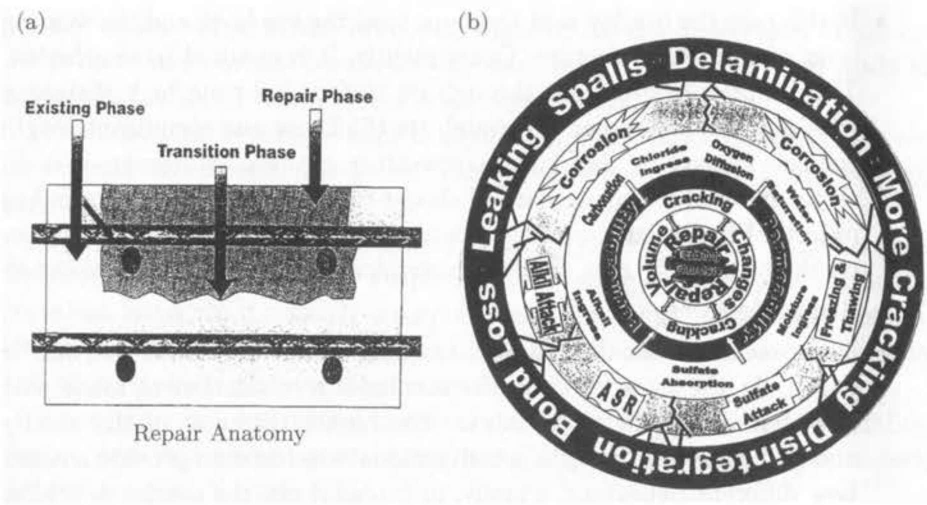


FIGURE 1. General problems of concrete repair: (a) repair anatomy, (b) physiology of repairs (after Emmons and Vaysburd [1]).

The main concern is the durability of the bond of the overlay on the repaired structure. A special emphasis will be put on the debonding of physico-mechanical origins. They are:

- the debonding "of mechanical origin", it is the result of the mechanical loading and straining of the overlaid structure,
- the debonding "of length changes origin", it is the consequence of the mismatching of the length changes of the overlay and of the substrate, for instance because of the shrinkage of the new concrete overlay applied on an old concrete substrate having finished its shrinkage.

These two debonding origins are illustrated in Fig. 2.

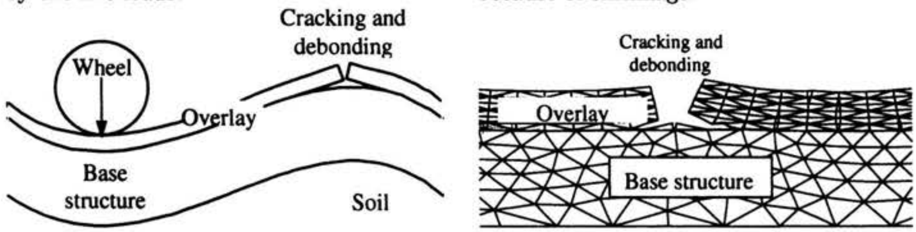
In both cases, debonding occurs from a **discontinuity** of the **tensioned overlay**. The discontinuity can be a crack through the overlay or the end of the overlay or a joint. It induces a peak of tensile stress perpendicular to the interface and a peak of shear stress which act to debond. A peak of tensile stress parallel to the interface is also present, but it has no or negligible effect [2, 3, 4, 5, 6].

An example of the built-in stresses developed at the interface by a discontinuity of the overlay is presented in Fig. 3. It is related to the case of a debonding of mechanical origin and two types of discontinuities are presented:

1. a neat cut through the overlay simulating a crack in a non-reinforced overlay (no force is transmitted through the crack),

(a) Debonding of mechanical origin, consequence of the flexural straining of the structure by the applied loads, especially by the live loads.

(b) Debonding of length changes origin, caused by the different length changes of the overlay and of the substrate, especially because of shrinkage.



The critical zone is apart from the applied loads, where the overlay is in tension. Debonding turns possible because of the cracking of the overlay.

Debonding is a consequence of the cracking of the overlay.
At each side of the crack, the peeling effect induces tensile stresses perpendicular to the interface.

In situ, these two causes of debonding superimpose their effects.

FIGURE 2. "Mechanical origin" (a) and "Length changes origin" (b) of debonding.

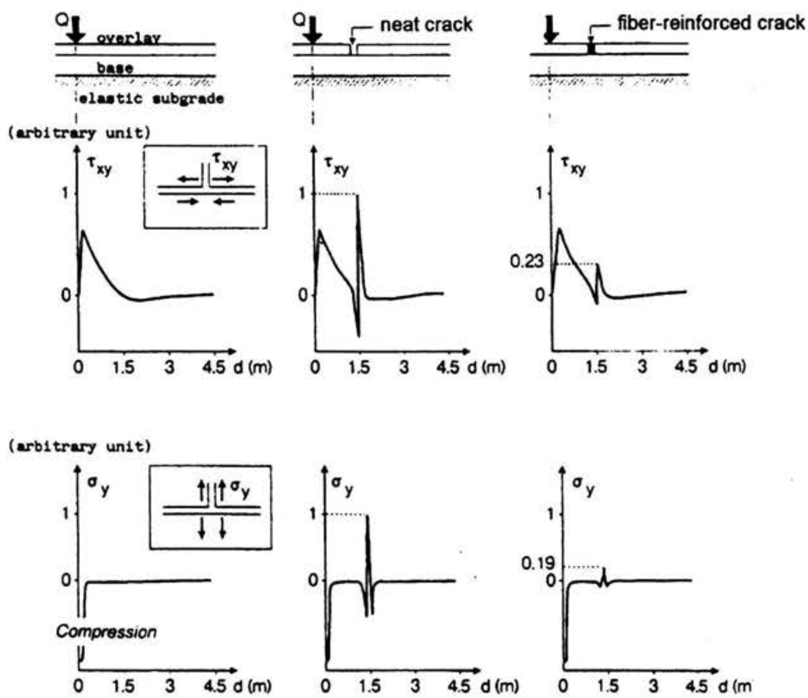


FIGURE 3. Peaks of stress induced at the interface by a crack and effect of a reinforcement of the overlay, example of a debonding of mechanical origin [5].

2. a lower elastic modulus section (one third of the modulus of the uncracked material) inserted in the overlay roughly simulating the case of a reinforced overlay.

It clearly illustrates that:

- sharp peaks of tensile stress perpendicular to the interface and of shear stress are induced by the discontinuity at the overlay-substrate interface, they act to debond;
- a reinforcement of the overlay, allowing to transmit forces through the discontinuity, decreases drastically the level of the stress peaks.

Moreover, a general trend is that the peaks of tensile and shear stresses at the interface are of the same order of magnitude. In the case of a contact between cement-based materials the tensile strength of the bond is usually about half of its shear strength. In these conditions debonding is expected to be initiated by tension perpendicular to the interface. The prevalent parameters for debonding initiation are then the tensile stress at the interface and the tensile strength of the bond.

The same observations are valid in the case of a debonding of length changes origin. Then the main origin of the tensile peak stress perpendicular to the interface is the "peeling effect" as illustrated in Fig. 4. It is the consequence of the unbalanced shear stresses at a the end of the bonded zone. It is often refereed to through a "peeling moment" defined as shown in Fig. 4. The trend of the overlay to curl, because of a non uniform shrinkage through its thickness, and, in the case of debonding of mechanical origin, the trend of the overlay not to follow the curvature of the substrate add their effects and increase the debonding tensile stress.

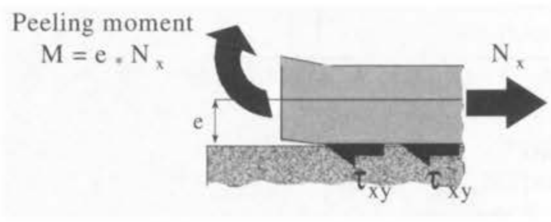


FIGURE 4. Peeling effect [6].

3. Pathology

3.1. Chemical or physico-chemical pathology

It is the consequence of the pollution of the substrate by chlorides or of the incompatibility of the overlay material.

If chloride polluted parts are left in the substrate, they will continue to activate corrosion.

If sulphates remain trapped in the repaired substrate or if they are brought by the overlay material, an ettringitic reaction will develop at the interface.

Finally, in the case of slabs on soil, if upward move of water from the soil is expected, an overlay acting as a barrier induces water accumulation at the interface which leads to debonding.

3.2. Mechanical and physico-mechanical pathology

There are two typical pathologies. On the one hand the cracking followed by the debonding-and-parcelling or the parcelling-and-debonding of the overlay. On the other hand, the curling of the overlay resulting in the lifting up and cracking of its corners.

3.2.1. Cracking and debonding of the overlay. A very significant example is the one of the Motorway 40 in Montreal (Canada). An experimental repair made in 1986 was thoroughly monitored by the team of P. C. Aïtcin of Sherbrooke University (Canada) [7, 8, 9, 10]. In the unreinforced overlay, cracks developed quickly and, within two years, the repair work had to be renewed. In the case of fibre reinforced overlays, cracks development slowed down quickly and soon stabilised. Twelve years later these repairs were still in good condition of use. For more details, see Secs. 8.2.2 and 11.3.1.

3.2.2. Curling of the overlay. The curling is the result of the non uniform shrinkage through the thickness of the overlay.

It was widely studied for slabs on soil. Particularly, it has been demonstrated that (cf. Holland, Walker [11], Féron [12, 13]):

- the curling increases with the drying shrinkage of the used concrete and with its elastic modulus;
- under the dead weight and loads of the lifted part of the slab, creep slowly decreases the lifting up and can bring it back to zero.

The same phenomenon is valid for the repair overlays. The lifting forces acting to debond can be very important and a high bond seems to be necessary to resist them.

Liftings are concentrated at the extremities and at the joints of the overlay. They can also, but rarely, be visible along cracks. For the user, they are felt as faulting joints. As illustrated in Fig. 5, they make traffic of wheel crafts less smooth. In turn, this traffic leads first to the distressing of the joint or

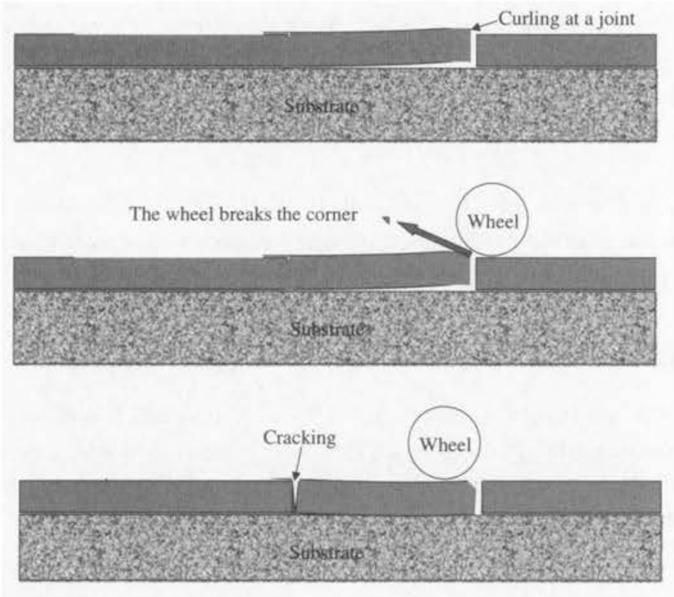


FIGURE 5. Curling of the overlay and associated distress.

crack lips, second to the cracking of the lifted and debonded portion of the overlay. That is the starting point of a quick deterioration.

4. Assessment of the structure to be overlaid

4.1. The surface repair of a slab on grade or a concrete pavement

The repair by thin bonded overlay cannot prevent the reflection of the substrate cracks. Consequently, only structurally sound slabs or pavements can be candidates for such application.

The inspection of the old structure will be carried out in two directions:

1. the nature and the extent of the surface distress,
2. the soundness of the structure.

4.1.1. Investigation of the surface distress. The surface distress is essentially unevenness, impact holes, scaling (disintegration of the surface concrete), spalling and pot-holes. It can be the consequence of chemical, physical (for instance freeze-thaw), mechanical attack or a combination of them:

1. Visual examination of the surface layer is the first step. It follows an idea of the type of attack, its intensity, its uniformity or not and the involved area.

2. Sampling (for instance by coring), to asses the cause(s) of the distress, the involved thickness and its uniformity or not.
3. Non destructive methods, from the surface, may complete the survey.

Usual tools for the assessments:

- For the chemical attack:
  - *on samples*: coloured reactants or chemical analysis;
  - *from the surface*: Surface Penetrating Radar can give information [14, 15, 16].
- For mechanical distress:
  - *on samples*: visual observation for cracking or eventual delamination, direct measurement of the compressive or tensile strength;
  - *from the surface*: detection of micro-cracking or other weakening by the indirect measurement of the elastic modulus with the "rebound hammer", *in situ* ultrasonic measurements, *in situ* permeability tests and penetration tests are also possible.

4.1.2. Investigation of the structural condition. Only minor structural defects are compatibles with thin bonded overlay repair of slabs on soil or pavements.

For concrete pavements, the Belgian Road Research Centre (CRR) [17] proposes the following chart for diagnostic and remedial measures (Tables 1 and 2). It can be easily transposed to the case of slabs on soil. The case of thin bonded overlay, designed by the code 5, is distinguished. In all cases, if there are faulting joints, they must be repaired prior to any overlaying.

TABLE 1. Remedial measures (CRR, 1991).

Code	Solution proposal
1	Continuing usual maintenance
2	Increasing of drainage efficiency
3	Patch repairs
4	Replacement of deteriorated slabs
5	***Thin adhesive overlay***
6	Thin non adhesive overlay
7	Replacement of the old overlay
8	Total reconstruction of the road structure

TABLE 2. Diagnostic and associated remedial measures (CRR 1991).

Visual observations	State of the substrate	Drainage	Number of vehicles per day		
			< 4000	4000÷18000	> 18000
Isolated cracks affecting less than 10% of the length of the road section. Low stair steps (< 3 mm). No settlement.					
	A or B	adapted	1	1	1
	A	unadapted	1	1 and 2	1 and 2
	B	unadapted	1 or 3		
Cracks affecting between 10% and 50% of the length of the road section. Stair steps (< 6 mm). Low settlements.					
	A or B	adapted	1 or 3	1 or 3 or 4	***5***
	A	unadapted	1 or 3	1 and 2 or 2 and 3 or 2 and 4	2 and ***5***
	B	unadapted	1 or 3 or 4	2 and 4 or 2 and ***5***	2 and 8
Cracks affecting more than 50% of the length of the road section. Stair steps (> 6 mm) or important settlements.					
	A or B	adapted	6 or 7	6 or 7 or 8	6 or 7 or 8
	A	unadapted	6 or 7	2 and 6 or 2 and 7	2 and 6 or 2 and 7
	B	unadapted	2 and 6 or 2 and 8	2 and 6 or 2 and 8	2 and 8

A = substrate is composed of quality and non polluted materials
B = substrate is composed of low quality and polluted materials

4.2. Bridge deck repairs

The thin bonded overlay technique is not expected to repair structurally cracked bridge decks.

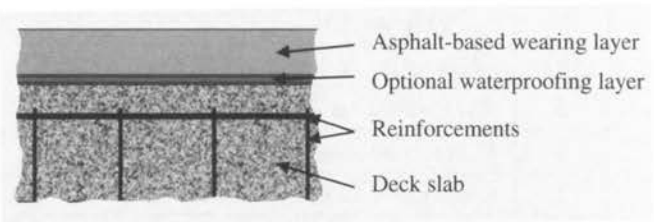


FIGURE 6. Typical cross section of a bridge deck.

The typical repaired distress is the replacement of the top layer of the structure not tight enough and polluted by chlorides. A consequence is the corrosion of the reinforcements with, possibly, delamination of the cover concrete.

A typical cross section of a bridge deck is presented in Fig. 6. Such distress is more frequent when the waterproofing layer is omitted.

4.2.1. Investigation of the structural condition. There must be no structural distress, but inside the volume of the future overlay.

4.2.2. Investigation of the top layer of the deck slab. It must be done with the least disturbance for the traffic, notably without removal of the wearing layer.

Available methods:

- Coring, as far as possible without cutting reinforcing steels. The cores will be used to state the type of distress and the involved depth.
- Surface Penetrating Radar [16]. It can be operated from the top surface of the wearing layer. It is sensitive to delamination, humidity content of the material and gives useful information on the corrosion probability. Recent developments of the technique provide reliable estimation of corrosion distribution along the reinforcements.
- Electric investigation of corrosion. It is designed as "half cell corrosion potential method". It can be used instead of or in complement of Radar. The principle is to measure the potential between the investigated reinforcement system and a special electrode (it is the "half cell") applied at the surface of the reinforced concrete. This potential is transformed into indication on the corrosion degree of the underneath reinforcement [18, 19, 20].
- The technique is reliable. Nevertheless it needs to uncover, at least in one point, the reinforcement system to connect it to the electrical device. Moreover, in the case of a deck slab, the wearing layer is an obstacle. It is then necessary to drill holes until the slab surface, through the covering layers, fill them up with electrolyte and dip the measuring electrode in the electrolyte pits.
- Surface Penetrating Radar again, impact echo or ultrasonic investigation are used to detect delaminations.

5. Overlay

In most cases, overlays are made of mortar or concrete. The size of the largest aggregate is expected to be smaller than 1/5 of the thickness of the layer. This mortar or concrete can be reinforced by fibres or, especially in the case of bridge deck repair, by steel bars or welded fabric. It can also be modified by polymers but this case will not be treated here. Finally, the overlay can be poured, on horizontal top surfaces, or spread in the other situations.

5.1. Choice of the overlay material

Physical compatibility

In the case of a slab on soil, if upward water move is expected in the structure, the overlay must keep it going until the upper surface. Two conditions must be fulfilled:

1. the overlay material must be permeable enough,
2. its pore system must be compatible with the one of the substrate, that is to say that the mean pore size of the overlay must be less or equal to the one of the substrate.

The overlay acts as a barrier, water accumulates at the interface and accelerate debonding.

Chemical compatibility

Don't pour regular Portland cements materials in contact with sulphate bearing materials. For instance, on substrates whose parts remain polluted by sulphates or by plaster after the preparation for repair.

In the case of upward move of aggressive water, the overlay material must resist to this aggression.

Length changes, of hydrical (shrinkage) or thermal origin, of the overlay

They are the enemies. Lower they are, better it is.

One could think that the same thermal expansion coefficient for the overlay and the substrate would be the best. Actually, the temperature changes of the outer layers, the overlay, are of larger amplitude than the ones of the inner parts, the substrate, and, in most cases, a lower dilation coefficient of the overlay is beneficial.

Elastic modulus and strength

The ideal solution would be a low elastic modulus, leading to low built-in stresses acting to debond, associated with a high strength providing a high resistance to cracking and consequently a decreased risk of debonding.

Actually, the elastic modulus and the strength of cement-based materials are not independent and the above solution remains "ideal".

The general solution is an overlay with the elastic modulus similar to the one of the substrate.

High performance material

It is possible. The physical compatibility and the elastic modulus-strength couple must be considered.

Fibre reinforcement

The reinforcement of the overlay by metal (high elastic modulus) fibres acts to delay debonding. Less than $40\,kg/m^3$ of regular steel fibres are enough for a significant effect. This point will be treated in detail in Sec. 11.

Non-metal fibres of low modulus are less efficient.

5.2. Overlay placement

5.2.1. Placement by pouring and levelling. It is the general case. It is convenient for the overlaying of horizontal upper surfaces. The mix must be fluid enough to get an intimate contact with the substrate. It must fill up all the cavities and micro-cavities at the surface of the substrate and also water must be available to be sucked into the superficial porosity of the old concrete. Typical values of slump for pouring on horizontal surfaces are more than 180 mm.

If vibration is necessary, the best solution is to use a vibrating levelling screed.

In the case of a fibre reinforcement, take care to step the lest possible on/in the fresh material. Indeed, each step pushes down to the bottom of the overlay all the encountered fibres, they will be later lost for the reinforcement effect. That is a general problem, not limited to overlays.

5.2.2. Spread concrete overlays. It is necessary when the surface to overlay is vertical, at the ceiling, or too much sloppy. In the following, the surface to overlay will be designated as "the wall".

There are two processes: the "humid mode" and the "dry mode".

Humid mode

The final mortar or concrete, with all its components including water and eventual fibres, is mixed and pumped to the spreading hose. Generally it results in high or medium W/C materials with a medium compaction and a medium quality of the bond with the substrate. But the final composition of the mix on the wall is identical to its initial composition in the mixing pot. The mix must fit the requirements of pumpability, then it is difficult to reach low W/C values. The projection speed of the mix at the hose is limited by the pumping process. It provides limited compacting energy when the mix crashes against the wall. For the same reason, limited energy is available to provide a tight contact with the wall that would result in a high bond.

Dry mode

All the components excluding water, but including admixtures (preferably as powders) and eventual fibres, are dry mixed and transported to the spreading hose by an air flow. The necessary water is spread separately from the hose tip. It mixes with the dry components on the way to the wall and on the wall. The dry mix is ejected at high speed from the hose, providing high compacting energy and only the necessary water for sticking to the wall and for hydration is provided. It results in a very compact material with very low W/C ratio and a high bond to the substrate. Due to the high speed at which the mix components are projected against the wall, many of them rebound and are lost for the overlay. The loss of material is not uniform for all the components of the mix, it is significantly greater for the largest aggregates and for the fibres. The proportion of loss depends on the skill of the hose holder. If the air pressure is too high or if the hose is too close of the wall, there is too much rebound. In the opposite case, it is the lighter components which, too much slowed down by the friction in the air, don't reach the wall or don't stick to it. The good solution is a compromise. With a skilled hose holder, the loss is about 20%, else it can reach 50%. As a consequence of this loss of material, a dry mode spreading site is very dusty and the hose holder must have special protection against the dust and the rebounding aggregates and fibres.

6. Bond and processing of the substrate

The bond is the result of a physico-chemical link and a mechanical interlocking between the substrate and the overlay.

The physico-chemical bond is at the nano level. It comes mainly from Van der Waals forces and from crystallisation of hydrates of the new concrete or mortar on pre-existing crystals of the old concrete, known as epitaxy. All these forces act at very short distance and vanish very quickly when cracking occurs.

The mechanical interlocking provides the largest part of the bond characteristics. Two levels must be distinguished: micro and macro.

The micro interlocking is the result of the crystallisation of hydrates of the new concrete overlay inside pores of the old concrete substrate. That is made possible by the sucking of water from the overlay into the pores of the substrate and crystallisation of the hydrates in these pores.

The macro level is the interlocking in the surface roughness of the substrate.

It is essentially these two levels of mechanical interlocking which provide the softening behaviour of a debonding overlay.

6.1. Characterisation of the bond

6.1.1. Bond strength tests. Such tests provide a single value: a "bond strength". It is the maximum load withstand before debonding under given conditions, divided by the area of the tested interface. There are tests for tensile strength and for shear strength of the bond. In actual overlay works, because of peeling, debonding is always initiated in tension perpendicular to the interface, the tensile strength is then the pertinent information. Since there is a relationship between tensile and shear strength, the reference to the second one is not meaningless. Figure 7 proposes a review of available tests.

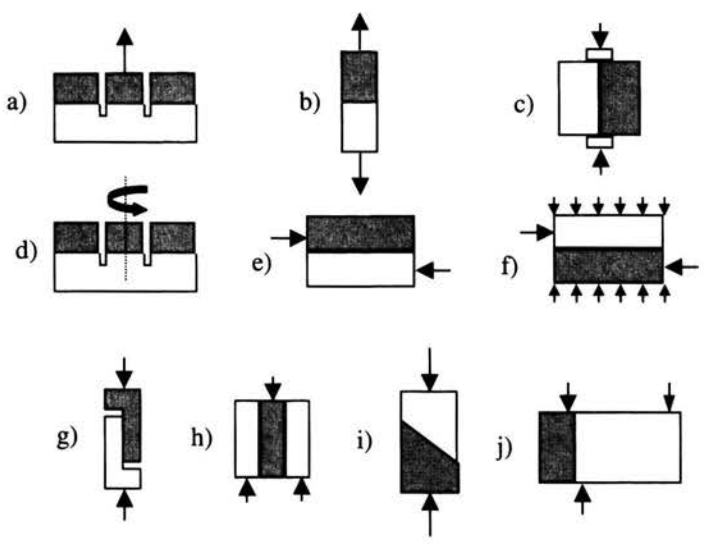


FIGURE 7. Bond strength tests.

Pull-off test (Figs. 7(a) and 8)

It is the most widespread test. It is a *in situ* test which provides a value of the bond tensile strength. A core drilling is operated until a deepness reaching about twice the thickness of the overlay. The core is not separated from the substrate structure. The top surface of the core is cleaned of all deposits and laitance and it is equipped with a glued steel plate. A jack, with a force measuring device and resting on the overlay by a tripod, grips the glued plate through a ball joint and pulls it off. If the core breaks at the interface, the test gives a value of the bond test. if it breaks in the overlay or in the substrate, the result is a lower bound value of the bond strength. This test is widespread because it provides *in situ* values, including the effects of the work site and environmental conditions, because it is easy to operate with little disturbance to the tested structure and because it is of low cost. A problem is the high discrepancy of the measured strengths. It results from the difficulty to obtain a perfect alignment of the glued plate and the jack device. The ball joint, necessary to manage with misalignments, is also a source of discrepancy. Debonding initiates at the weakest location of the interface and, afterwards, the ball joint allows it to propagate in flexion with lower efforts than in pure tension.

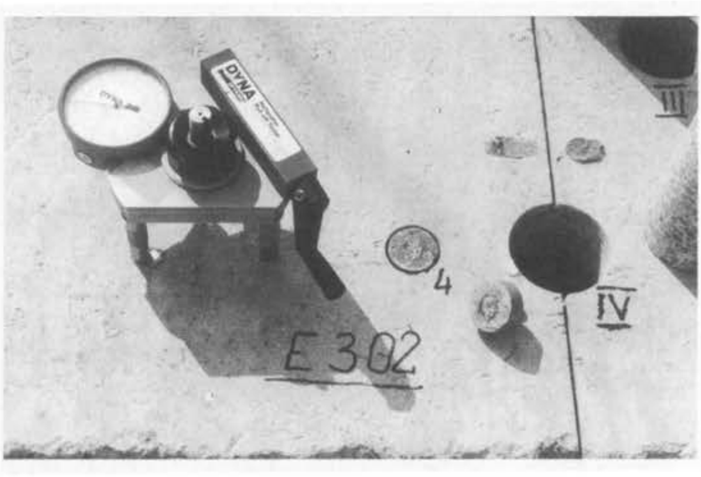


FIGURE 8. Pull-off test.

Direct tensile strength (Fig. 7(b))

For most significant result, it must be operated without ball joint. The two end faces are ground parallel and glued in place with quick hardening adhesive on metal plates (AU4G aluminium alloy) fastened to the non-hinged testing machine plates. In these conditions, the measured value actually represents the average bond on the total area of the tested interface. Such a test is a laboratory test. Its transposition *in situ* in the shape of a pull-off test with no ball joint is difficult.

Splitting tensile test (Fig. 7(c))

It is an alternative solution.

Shear tests (Fig. 7(d)-(j))

The torsion shear test (d), a transposition to torsion of the pull-off test and developed by J. Silfwerbrand, is an *in situ* test. All the other tests are laboratory tests.

The test (f) is the transposition of the Cassagrande test for soils. Several tests with different compression stresses provide the plot of the σ–τ domain beyond which there is debonding. The slant test (i), for each angle of the interface, provides one of the points given by the test (f). For bonded overlays, such solicitation of the interface, shear plus **compression**, is frequent in the propagation phase of debonding, but it is very seldom in the initiation phase. Or all the tests above provide information worth only for the initiation phase.

6.1.2. Fracture mechanical characterisation of the debonding at the interface. The debonding initiates in mode 1 and propagates in a mixed mode: mode 1 + mode 2. An essential information is the softening behaviour of the debonding interface in each of these two modes. The usual fracture mechanics test developed to investigate the propagation of a crack are applied here to the study of the propagation of debonding along an interface. All are displacement controlled tests and need a high technology testing equipment, consequently they are exclusively laboratory tests. They are reviewed

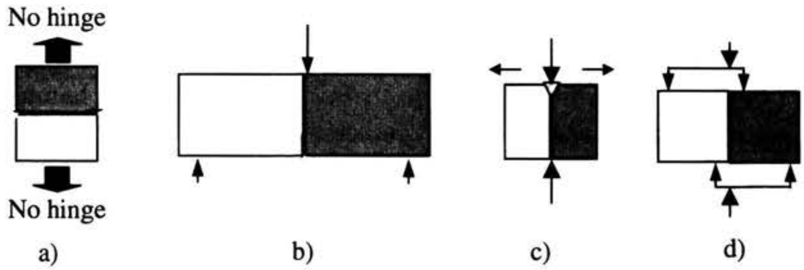


FIGURE 9. Fracture mechanical characterisation of the debonding at the interface.

in Fig. 9. The fittings (a) to (c) are related to mode 1 and the fitting (d) allows to investigate mode 2.

The test (a) is the fundamental test. It is also the most difficult to perform. It is performed in the non-hinged mode (see above in Sec. 6.1.1) and provides the true post-crack (or post-debonding initiation) softening curve of the tested interface, that is to say the relationship: residual stress versus opening (σ–w) (see Sec. 9.2). It is designated as "direct tension test on notched sample".

For mode 1, the tests (b) and (c) are indirect (structural) tests. They provide a global information along an area where different debonding opening are presents.

To investigate mode 2, the test (d) is theoretically perfect, but it is very difficult to perform.

6.2. Preparation of the surface to be overlaid

First of all, any polluted, micro-cracked or weakened, non durable or non-adhesive material must be removed until the sound material of the substrate is reached. Second, the obtained surface must be carefully cleaned before the overlay placing.

Table 3 presents the methods for concrete removal (Silfwerbrand [21]). They are ranked from the least to the most powerful.

At the one end, sand blasting which is not expected to have a "depth action" removes the very superficial layer of the substrate. It doesn't create significant roughness. It efficiently takes off surface pollution (for instance from oil leakage), laitance and most superficial scaling. It is convenient in the case of overlaying a sound structure for lining or strengthening.

At the other end, water jetting can remove great depths of materials. It is the most efficient method for surface preparation and also the most expensive. It is selective in the way that it removes the weakest volumes of material, it is harmless for the reinforcements steels and in addition it cleans them of adhesive remainders. It creates significant and deep roughness.

The jack hammer removing causes unavoidable micro-cracks which make a zone of weakness under the surface to overlay. Heavy jack hammers are more efficient, but create more micro-cracking.

When a uniform depth of non-reinforced material must be removed on a large area, milling (or scarifying) plus flushing with high pressure water provides a very good quality surface, with a medium roughness and very few micro-cracks.

The final cleaning is essential. Even in the case of water jetting, Silfwerbrand proposes to clean at once after the removal operation to flush away all

TABLE 3. Methods for concrete removal (from Silfwerbrand [21]).

Removal method	Principle behaviour	Depth action?	Important advantages	Important disadvantages
Soundblasting and shotblasting	Blasting with sand or steel balls	No	No microcracking, no dust	Not selective
Flame-cleaning	Thermal lance	No	Effective against pollutions and painting	The reinforcement may be damaged, smoke and gas development, not selective
Milling (scarifying)	Longitudinal tracks are introduced by rotating metal lamellas	Yes	Good bond if followed by water flushing	Not selective
Pneumatic (jack) hammers, hand-held or boom-mounted	Compressed-air-operated chipping	Yes	Simple use, large ones are effective	Damages reinforcement and concrete surface, poor working environment, not selective
Grinding	Grinding with rotating lamella	No	Removes uneven parts	Dust development, not selective
Explosive blasting	Controlled blasting using small, densely spaced blasting charges	Yes	Effective for large removal volumes	Difficult to limit to solely damaged concrete, not selective
Water-jetting (hydro-demolition)	High pressure water jet from a unit with a movable nozzle	Yes	Effective, selective, does not damage reinforcement or concrete, improved working environment	Water handling, removal in frost degrees, costs for establishment

re-deposit of loose particles and immediately before overlaying to make sure that surface is free from sand, oil, dust or any other pollutant with origin from the environment or the construction traffic.

6.2.1. Characterisation of the roughness. It can be characterised by simple tests giving a comparative index. A much widespread test method is the sand area method [22] (Fig. 10), in which sand of known volume V is spread over the concrete surface to form a circle until all sand has settled in the surface cavities. The roughness R_t can be calculated from the diameter d of the circle using the following relationship:

$$R_t\ [\mathrm{mm}] = \frac{40\,V\ [\mathrm{cm}^3]}{\pi\,d^2\ [\mathrm{cm}^2]}.$$

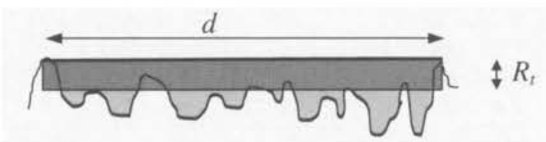


FIGURE 10. Determination of surface roughness using the sand area method (Kaufmann [22]).

The surface roughness is better described by two parameters: the "double amplitude" and the "wave length" as proposed by Silfwerbrand and defined in Fig. 11.

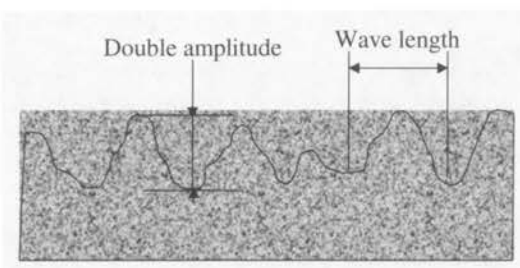


FIGURE 11. Parameters describing surface roughness (after Silfwerbrand [21]).

Water jetting gives high double amplitude roughness, in the vicinity of 10 mm or more depending on the adjustment of the pressure. Sand blasting doesn't create significant roughness, the final double amplitude is usually significantly less than 1 mm.

6.2.2. Incidence of the roughness and of micro-cracking. From the analysis of the results of numerous years of repair experience, Silfwerbrand [21, 23] proposed different comparisons that can be summed up as in Table 4. He also noticed that with high roughness, air pockets are easily entrapped in the valleys of the interface. High care must be taken to prevent it. Consequently, a high double amplitude associated with a short wave length is detrimental because it increases the risk of ill filling of the interface valleys.

TABLE 4. Incidence of the roughness and of micro-cracking: pull-off tests (after Silfwerbrandt [21]).

Interface treatment	Roughness double amplitude	Presence of micro-cracking	Mean pull-off strength of the bond
Sand blasting	0.4 mm	No	≈ 2 MPa
Scarifying	?	?	2.3 MPa
Jack hammer	?	Yes	≈ 1 MPa
Water jetting	7.7 mm	No	≈ 2 MPa

It is clear that a high roughness is not the prominent parameter to achieve high bond strength.

To complete the scope:

- As a confirmation, *in situ* results from the author and results from the full scale test campaign carried out in Zmigrod, Poland, (Brandt *et al.* [24], see Sec. 8.2.2) sand blasting preparation of the surface also ended into a tensile bond strength in the vicinity of 2 MPa.
- Laboratory results from Granju *et al.* [25] demonstrated that pouring the overlay on the sawn surface of an old concrete yielded a very high bond.

Hence, one can conclude that the main part of the bond is developed at the nano and micro level, by chemical links and by precipitation of hydrates of the overlay inside the superficial porosity of the substrate.

These results are related to tensile debonding (mode 1). Figure 12 shows that when mode 2 is involved (including shear debonding), the roughness may have a more significant influence. However, if the sign of the shear stress changes, for instance because of alternated loading induced by traffic, at each change of sign, the friction on the roughness slopes passes through zero.

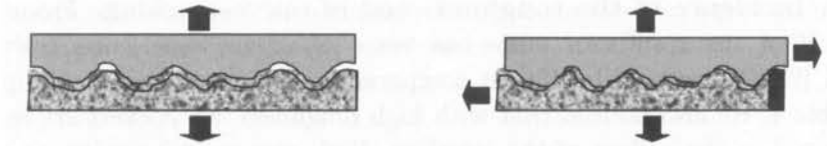


FIGURE 12. Different incidence of roughness in the case of tension or shear debonding.

6.2.3. Bonding agents and moisture of the interface. This point was thoroughly investigated by Saucier and Pigeon [26]. Other authors such as Schrader [27] made similar investigations which lead to the same conclusions. Various tests confirmed these findings.

It is now established that the solution providing the best price-efficiency ratio is:

- a clean and sound surface,
- no bonding agent,
- moisture condition: dry surface.

Cleanness of the interface is essential, it was already discussed.

Bonding agents can range from a cement slurry to an epoxy compound via a latex-based layer. Although the use of a bonding agent is a widespread practice, it is not advised. It ends into two interfaces, one with the substrate and one with the overlay, and it can be a weak layer. Consequently, although its intrinsic qualities, it multiplies by three the risk of defect. The statistical result is an advantage for no bonding agent.

Moisture of the surface to be overlaid has been for a long time subject to discussion. It is now clearly established that the quality of the bond widely depends on the ability of water from the overlay to be sucked inside the superficial pore system of the substrate. Due to that, hydrates of the overlay can precipitate inside the pores of the substrate, forming a continuum of strength carrying hydrates through the interface. In these conditions, the contact is so tight that only indirect signs allow to locate it on SEM polished sections (Granju *et al.* [26]). Moreover, pre-saturation of the substrate makes it swell. Its future unswelling will decrease its length mismatching with the shrinking overlay.

If the surface is soaked, with visible shining water, there is no sucking and the W/C ratio is locally increased by this water at the interface; it results in a very poor bond.

If the substrate is dry:

- it sucks a high quantity of water from the overlay; that creates no problem if the water providing ability of the overlay is large enough, in other words if its W/C ratio and thickness are high enough (for instance $W/C = 0.5$ and thickness $\geqslant 50$ mm); otherwise a dry substrate is detrimental to the good hydration at the interface;
- the substrate swells less than in the case of a previous soaking and the beneficial effect of the unswelling is smaller.

7. Shrinkage: cracking and curling

This point was mentioned in Sec. 3 "Pathology".

Shrinkage-induced cracking was and is still extensively investigated. The last developments are compiled in the report of the RILEM Technical Committee 181-EAS "Early age Shrinkage" [28]. Because shrinkage develops slowly in an ageing material, the built-in stresses leading to cracking are continuously modified by the simultaneous ageing, creep and relaxation. Linear elasticity is not convenient. In this context, the non uniformity of shrinkage through the depth of the overlay which is responsible for curling must also be accounted for.

Restrained curling, by the overlay-substrate adhesion, can induce very high stresses. Early cracking, otherwise considered as detrimental, can relax the restrained curling debonding forces.

7.1. Modelling

Any modelling is a real challenge. It relies on the modelling of shrinkage with all its parameters and the modelling of the mechanical response with the difficulties listed above. F. Saucier wrote in 1997 that, at this time, "develop a realistic model for concrete repair [at this time (1997)] is not yet possible" [29]. Nevertheless, models were developed, for instance by the teams of Wittmann [30], Baluch [31], and Féron [12, 13].

Taking information from the results of these models confirms that:

- water exchange between the overlay and the substrate cannot be neglected,
- increase of fracture energy of the overlay or/and decrease its elastic modulus delays cracking of the overlay,
- optimised composition of the overlay delays or prevents its cracking and also delays its debonding,
- debonding is delayed when shrinkage is decreased and/or the strength and fracture energy of the interface is increased.

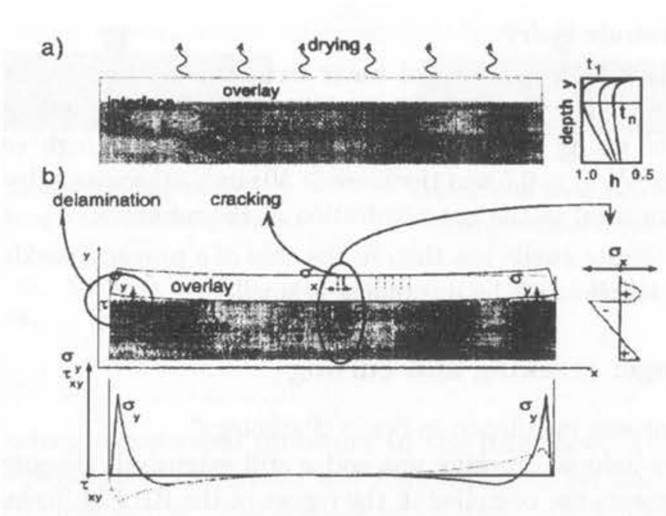


FIGURE 13. Schematic representation of the complex state of stress in a combined system of overlay and substrate after a certain period of drying (after Wittmann's team [30]).

7.2. Experiment

For a thorough investigation of the restrained shrinkage and the associated creep an relaxation, a very refined test was initially developed by Kovler [32]. It consists in a device allowing to impose the desired drying conditions and the desired constraint to a bone-shaped cement based sample and, at the same time, to monitor the resultant tensile stress caused in the sample by the imposed constraint.

More simple tests are also available. The most wide-spread is the ring test (Grzybowski and Shah [33]). The only information that it provides is the time of cracking occurrence.

An other test (Vaysburd *et al.* [34]) measures the curling of a 1321 mm long overlay specimen sealed on all its faces but its upper face. One specimen is free to strain, another one was poured onto an adhesive metal plate imposing a restraint to straining. The first specimen informs on the curling caused by the non uniform shrinkage. The subtraction from the curling of the second specimen informs on the restraining force.

These tests have a handicap, namely they cannot include non-negligible, water exchanges with the substrate.

Realistic tests must include a concrete substrate. As cracking is strongly dependent on the restrained length, the test specimens must be longer than the mean crack-to-crack distance. That leads to very large test specimens.

test specimens, 2 m long or more. An interesting solution is the "box specimens" developed by Vaysburd *et al.* [34].

8. Debonding mechanisms

8.1. Brief recall

It has been seen in Sec. 2 that:

- debonding cases can be classified according to two types: of "mechanical origin" and of "length changes origin";
- whatever the origin, the fundamental debonding mechanism is the same;
- debonding always starts from a discontinuity (a crack, a joint or the end of overlay) in an overlay under tension, it is initiated by built-in stress peaks induced by the discontinuity; because of the peeling effect a significant peak of tensile stress perpendicular to the interface is always present;
- in the case of cement-based contacts, the shear strength of the bond is about twice its tensile strength, then debonding always initiates by tension perpendicular to the interface;
- finally, a reinforcement of the overlay, with fibres or with steel bars delays or even prevents debonding.

The illustration of these points is shown in Figs. 2, 4 and 14.

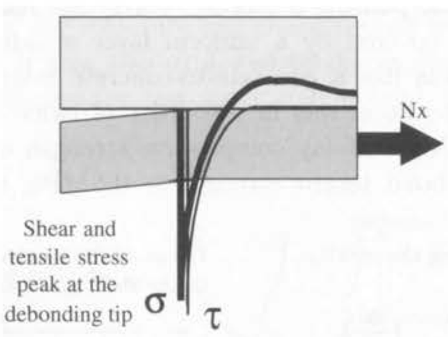


FIGURE 14. Debonding stress peaks.

8.2. Experiments

One can classify them in in two families: laboratory experiments and full scale or *in situ* experiments.

8.2.1. Laboratory experiments. Numerous and various types of laboratory experiments were performed in the world.

In the following we will present experiments carried out in Laboratoire Matériaux et Durabilité des Constructions (Université Paul Sabatier/INSA) in Toulouse, France, focussing on the debonding mechanism (J.-L. Granju, H. Chausson, A. Turatsinze, H. Farhat) [4, 5, 6, 35, 36, 37, 38]. More precisely, tests were developed in order to eliminate or drastically diminish the influence of all the parameters not strictly involved in the debonding mechanism.

These undesirable influences are:

- the autogenous length changes of the substrate, its swelling when it sucks water from the overlay and its future unswelling,
- the continuation in the substrate, with no debonding, of a crack initiated in the overlay,
- the discrepancy associated to the limit of fabrication repeatability of concrete substrates, one for each test specimen,
- at last and not the least, all time-dependent phenomenons: shrinkage, hardening during the test time, creep and relaxation, curling due to non homogenous shrinkage whose restraint by the bond to the substrate may induce significant stresses very difficult to estimate.

The solution relies on the use of metal substrates. They were made of steel hollow shapes (see Fig. 15) designed and treated to simulate concrete substrates. Their inertias were in accordance with the ones of concrete substrates of same sizes. The interface with the overlay was milled rough and treated by repetition of the cycle-pouring a mortar overlay, let hardening, debonding-until the surface is covered by a uniform layer of adhesive cement-based material. Then it was like a concrete-to-concrete interface, especially the shear strength of the bond was in the order of twice its tensile strength. Actually, with a 50 MPa 28-day compressive strength mortar as overlay, it was measured: the bond tensile strength ≈ 0.5 MPa, and the bond shear

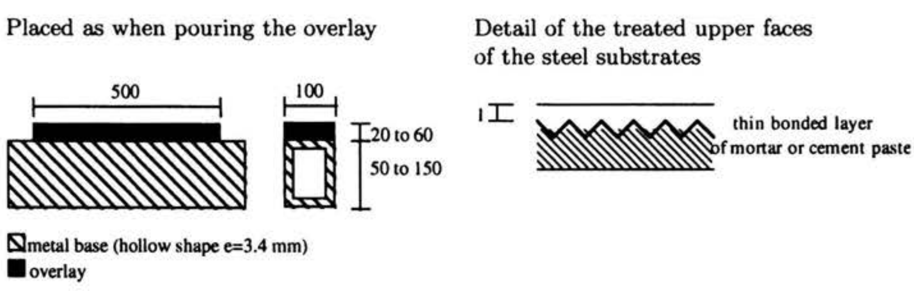


FIGURE 15. Metal substrates.

strength ≈ 1 MPa. It is the strength of a poor bond, it can be considered like the average bond in areas where *in situ* conditions were not perfect: pollution of the interface by the work-site vehicles, ill filling of the roughness valleys, and so on. The test samples were all 100 mm wide with an overlay 500 mm long. The height of the substrates was varied from 50 to 150 mm and the thickness of the overlays from 20 to 60 mm.

Investigation of the debonding of mechanical origin

The above composite specimens were tested in flexure, usually three points flexure with the overlay on the tension side as illustrated in Fig. 16. The rests of the flexure fitting applied on the overlay itself to prevent debonding from the extremities. The tests were performed at early age, 7 days, in order to neglect the effects of shrinkage.

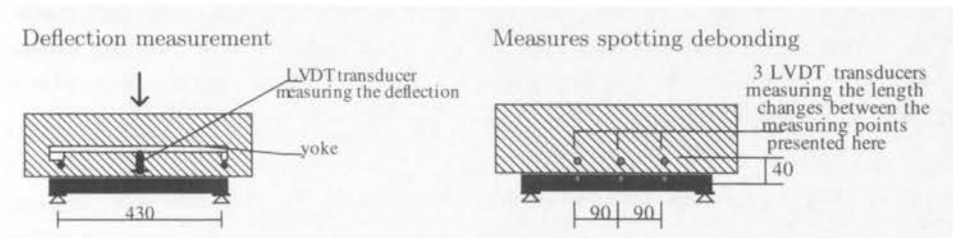


FIGURE 16. Debonding of mechanical origin: test fitting, example of debonding spotted by 3 LVDT transducers.

The curvature of the structure was characterised by the deflection measured at mid-span. It was also exploited to detect cracks occurrences (see Fig. 17(a)). Depending on the test series, debonding initiation and propaga-

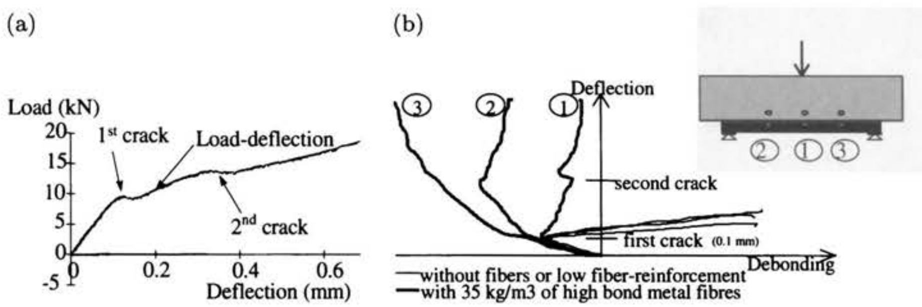


FIGURE 17. Debonding of mechanical origin: an example of test results; (a) load-deflection curve and spotting of cracks; (b) spotting debonding, here the signals of 3 LVDT versus deflection.

tion were spotted by 3 LVDT transducers or by 5 ohmic strain gauges or a set of breaking electricity conductive links spanning the overlay-substrate interface. Visual observation with a magnifying device completed the information.

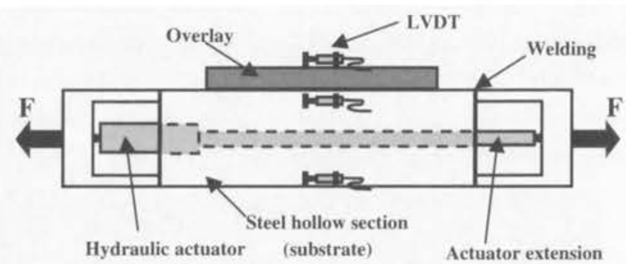
A typical result (in the case of a monotone loading with no pre-cracking) is presented in Fig. 17. It illustrates the behaviour of two types of overlays: one made of plain mortar, the other one reinforced with 35 kg/m^3 of high bond metal fibres.

As long as there is no debonding, the devices spanning the interface measure a compression. Debonding makes their signal turn towards tension. Then, in Fig. 17(b), propagation is characterised by the rightwards move of the plot. One sees that, without fibre, debonding occurs at the same deflection as the first crack and instantenously propagates over all the investigated length along the interface. With the fibre reinforcement considered here, the first crack initiated debonding but there was no propagation. A second crack, which opened in the vicinity of LVDT 2, brought an other debonding initiation at this location, but still with no significant sign of propagation. Obviously, the fibre reinforcement of the overlay had a beneficial effect.

Investigation of the debonding after changes of the initial length

The effect of the shrinkage of the overlay is simulated by the stretching of the metal substrate, Turatsinze *et al.* [38]. The length change mismatching is similar in both cases. The test setting is illustrated in Fig. 18. The stretching agent is an hydraulic actuator placed inside the metal hollow substrate.

(a)



(b)

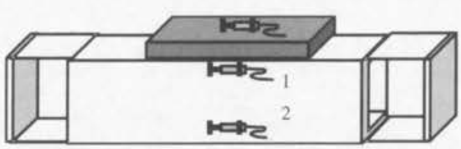


FIGURE 18. Stretching base – experimental device: (a) with the actuator, (b) view of the substrate and the overlay alone.

The actual strain at any level in the substrate and the overlay, notably at the interface, is calculated from the reading of LVDT 1 and 2 with the plane assumption of the sections. A third LVDT is placed on the top surface of the overlay at mid-length. If the first crack of the overlay occurs at mid-length as it should be, it allows to monitor its opening, otherwise its information is of limited use. In addition, cracking is monitored by optical means, with a 25 times magnifying "crack microscope".

This test method has an enormous advantage: the test lasting less than one hour, all the time-dependent effects can be neglected. Consequently, the analysis of the results is simple and wins enormously in reliability. Indeed, until now the time-dependent effects, hardening, creep and relaxation, are predictable only roughly and when their introduction in the analysis chain is necessary, they are prominent factors of uncertainty. Moreover, this test method allows to chose the test time, actually 7 days as for the flexure tests. Depending on the will, drying shrinkage can be prevented, by sealing the overlay, or not.

8.2.2. *In situ* and full scale experiments. Once again, they are numerous. Here will be presented an *in situ* concrete pavement repair in Montreal, Canada, and a huge programme of full scale tests carried out conjointly by Polish teams at the Institute of Fundamental Technological Research, Warsaw, and at the Institute of Roads and Bridges, Wroclaw and Zmigrod, in co-operation with a French team at Laboratoire Matériaux et Durabilité des Constructions (Université Paul Sabatier/INSA), Toulouse.

Experimental repair in Montreal [7, 8, 9, 10]

It was carried out on Motorway 40. It is a concrete Motorway, three lanes in each way, withstanding a traffic of 30 000 vehicle per day. The experimental repair was performed in 1986 with the aim to compare the efficiency of different types of bonded overlays and especially the effect of a fibre reinforcement. The great interest of this experimental repair is in the fact that it is thoroughly documented. Its conception, the preparation of the substrate, the placing of the overlay were supervised by the team of P. C. Aïtcin (P. C. Aïtcin, G. Chanvillard C. Lupien) who, further, ensured the monitoring of its behaviour within a 12-year period. On a total length of 134 meters, each investigated overlay system covered a section of about 20 m in length. The different types of overlays systems accounted for and compared included plain concrete ones (100 mm thick) and others reinforced with 22 to 34 kg/m^3 of steel fibre (75 mm thick). Several types of steel fibres were tested: hooked ended or undulated, of circular or rectangular cross section, all 50 mm long.

The effect of a connection between the overlay and the base pavement by steel nails was also investigated. These ones were 67 mm long and previously gun driven to half of their length into the old pavement. No nail was driven in the central lane, the two other lanes were nailed, one with a nail each 300 mm, the other one with a nail each 450 mm. The interface was prepared by sand jetting to rub off all oil stains, other impurities and all loose material. In the case of the plain concrete overlay (100 mm thick against 70 mm for the fibre reinforced sections), 25 mm of the old concrete pavement were removed by scarification. All the overlay was bonded with a thin cement grout. A sketch drawing of the different test sections is presented in Fig. 19.

The cracks were observed visually. The thinnest detectable, 1/10 mm wide or a little less, were made visible by a light wetting of the surface. The crack growth was quantified by a "cracking index" defined as the total length of observed cracks per unit length of lane.

Eventual debonding was detected by two methods:

1. With a chain rake dragged along on the surface of the overlay. It sounds differently on the debonded areas.
2. By thermographical investigation. In the morning, when the surface of the pavement was cool, heat up-coming from the soil is stopped or disturbed by the air void made by local debonding. A thermographical video system makes these disturbances visible.

This investigation showed that the chain rake is a sensitive and reliable tool.

Full scale test programme in Poland [25, 39, 40]

The programme was started in 1999 with the aim to have fine measurements on slabs overlaid with plain or fibre reinforced concretes. The Bridge, Concrete and Aggregate Research Centre in Zmigrod provided an ideal site for large scale tests. It has the necessary back-up facilities and its main test stand is provided with a data collection and acquisition system which can measure displacements, strains, stresses, forces, weights, moments, temperatures, etc. The measuring system is composed of a Hottinger Baldwin Messtechnik UPM 100 measuring device which allows to measure 100 quantities simultaneously and which can work with strain gauges, induction gauges, force gauges, thermocouples, etc. A computer with software controls the different devices and allows to record and analyse all measured data.

Nine slabs were investigated, three for each of the following repair concretes: plain, reinforced with 30 and with 45 kg/m^3 of steel fibres. Each base slab was 150 mm thick, 1.5 mm in width and 5.25 m in length, overlaid by a 70 mm repair layer. The substrate slabs were left to harden 6 months before overlaying. The surface was prepared by sand blasting and water flushing,

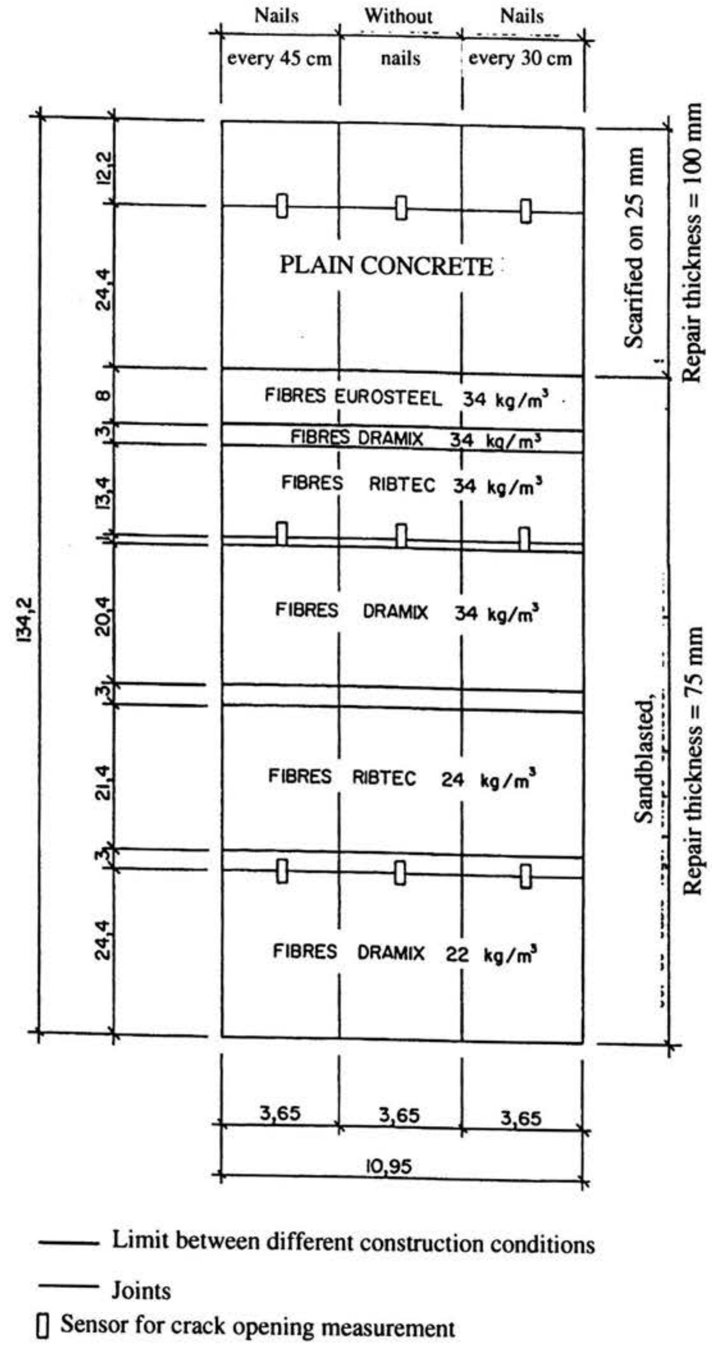


FIGURE 19. *In situ* experiment rehabilitation: details of the different construction conditions.

the substrate slab was soaked with sprinkling water, the surface was allowed to dry and the overlay was poured without bonding agent. After some time, the overlay was notched at mid-length with the hope that it would initiate a shrinkage crack (see Fig. 20).The whole was then left to harden for more than one year.

FIGURE 20. Zmigrod tests: notching the overlaid slabs.

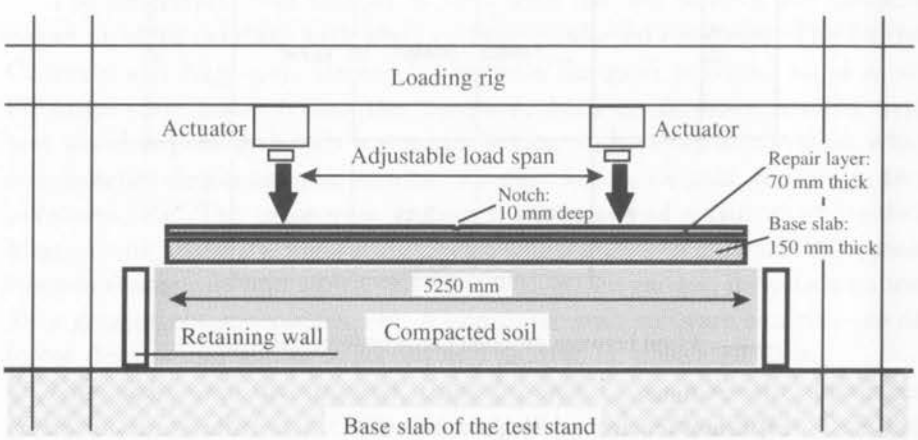


FIGURE 21. Full scale test fitting in Zmigrod (Poland).

FIGURE 22. Placement of the soil, compacted layer after layer.

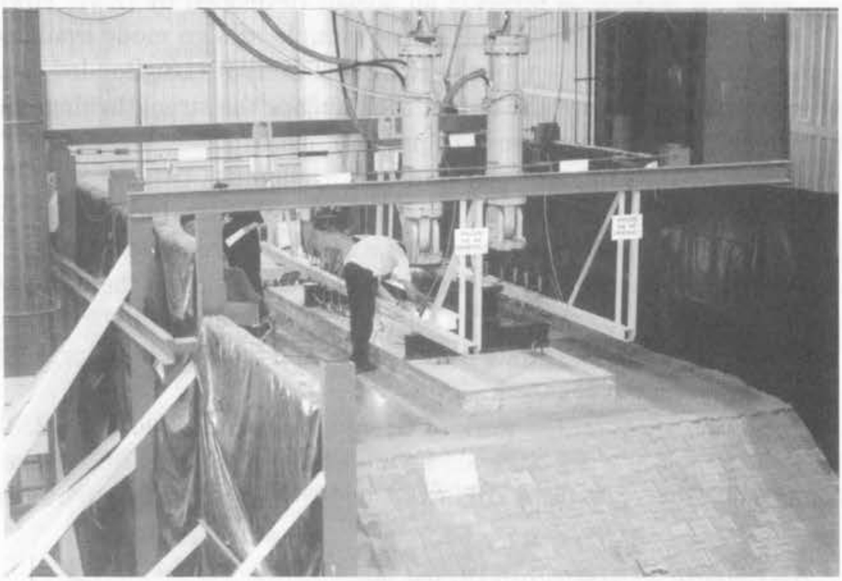


FIGURE 23. Slab in place, during a test.

A 2 m high volume of compacted soil (E modulus in the vicinity of 120 MPa) was installed under the testing rig.

At the time of each test, the top layer of the soil, about 0.3 m high, was re-compacted and its density controlled to have the expected E modulus. After that, the overlaid slab was transported and seated on the soil. To have a good and repeatable rest, it was necessary to rest the slab on a layer of lean mortar, dispositions were taken to prevent that this later has strengthening effects.

A frame resting on fixed points held deflection gages to monitor the moves and deflections of the repair top-surface. An impact-echo device was used to detect the debonding and its propagation.

The test fitting is sketched in Fig. 21. The placing of the compacted soil and the slab in place are illustrated by the photographs of Figs. 22 and 23.

9. Calculation and modelling

Available analytical calculations provide only the value of the stress peaks at a discontinuity of the overlay. They are very complicated and usually end in abacuses.

Such calculations were developed notably by Biggwood *et al.* [2] and by Fowler *et al.* [3]. Figure 24 presents an abacus developed by D. W. Fowler.

At the present time (2003), there is no "simple" design mode available for the practitioner. It is the aim of the RILEM TC "193-RLS: Bonded cement-based material overlays for the repair, the lining or the strengthening of slabs or pavements", presently on work to propose one.

Today, only finite element calculation is available.

To be realistic, it must rely on the fracture mechanics. Indeed, debonding is the consequence of crack in the overlay, then crack propagation is essential. Moreover, the propagation of a debonding is nothing else as the propagation of crack following the interface. The softening behaviour, it will be designated as "interlocking", of crack through the overlay and of the debonding interface are essential parameters.

This Section relies on the work of Granju, Sabathier *et al.* [41, 42, 43]. It enlightens the features that a realistic modelling must necessarily take into account. The proposal will be confirmed by comparison with experiment.

9.1. Algorithm of the modelling

For the purpose of crack or debonding propagation, it is usual to control the propagation from the stress state calculated at the first node beyond the crack tip or beyond the debonding tip as sketched in Fig. 25. Such a method

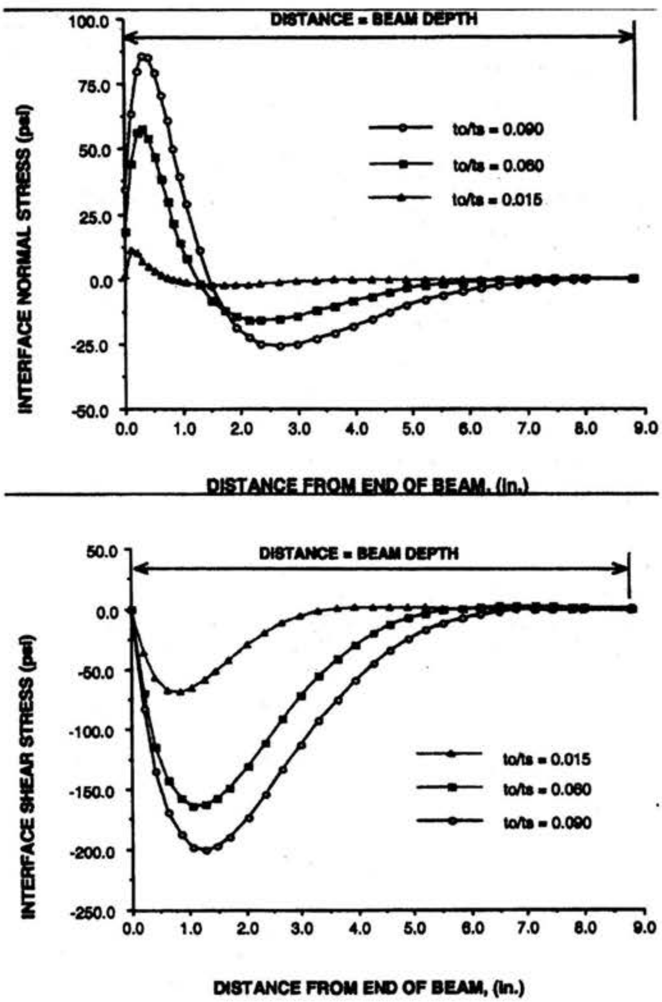


FIGURE 24. Peak stresses at the end of an overlay, from Fowler *et al.* [3]; t_o/t_s = overlay thickness/substrate thickness; E_o/E_s = elastic modulus of the overlay/elastic modulus of the substrate.

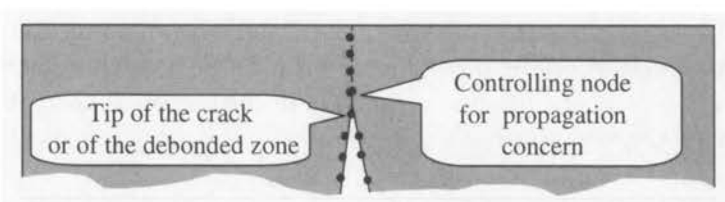


FIGURE 25. Finite element calculation: node controlling a crack or a debonding propagation.

avoids to control the propagation by the stress state calculated at a node, the tip of the crack or of debonding, where the theoretical stress can reach an infinite value. On this basis, crack tip or debonding tip propagates to the next node when the stress state at the controlling node no longer satisfies the stability criterion (which depends on the material or on interface). Interlocking is taken into account by closing forces imposed between the nodes facing each other along the opened crack or along the debonded zone. These closing forces depend on the relative displacements (perpendicular and parallel to the crack or to the debonding plane) between each couple of facing nodes. An alternative method is to model the crack or debonding path with adjustable stiffness elements. At each calculating step, the stiffnesses corresponding to mode 1 and to mode 2 displacements are adjusted to provide the required closing forces.

In all cases, the closing forces are known from the post-crack softening curves relating, for mode 1, the post-crack tensile stress with the crack-opening and, for mode 2, the post-crack shear stress with the relative sliding. These curves can be obtained either directly from the tests described in Sec. 6.1.2 or estimated from literature.

Finite elements calculations are often mesh-dependent. The mesh-size must be varied from coarse to finer until the calculated results turn independent from the mesh size.

9.2. Interlocking

9.2.1. Fundamentals. The consequence of interlocking is the softening behaviour. It acts at two levels:

1. the micro level, it corresponds to the smaller openings and is always present; much probably it involves a large part of bridging;
2. the macro level, its extent depends on the roughness of the crack or interface; the more pronounced the roughness, the wider the expected opening is before interlocking vanishes.

Because debonding propagates in mixed mode, mode 1 plus mode 2, residual stresses in both the normal and the tangential debonding direction and their interaction (as it will be evidenced later on) must be accounted for. Figure 26 shows their typical evolution as a function of the opening w and the relative sliding s of the debonded interface. It also shows how can be taken into account a fibre reinforcement, then only mode 1 is concerned.

In the case of rough interfaces, for instance obtained with water-blasting, high interlocking forces lasting up to large debonding openings, and consequently a significant effect on the debonding propagation, are to be expected.

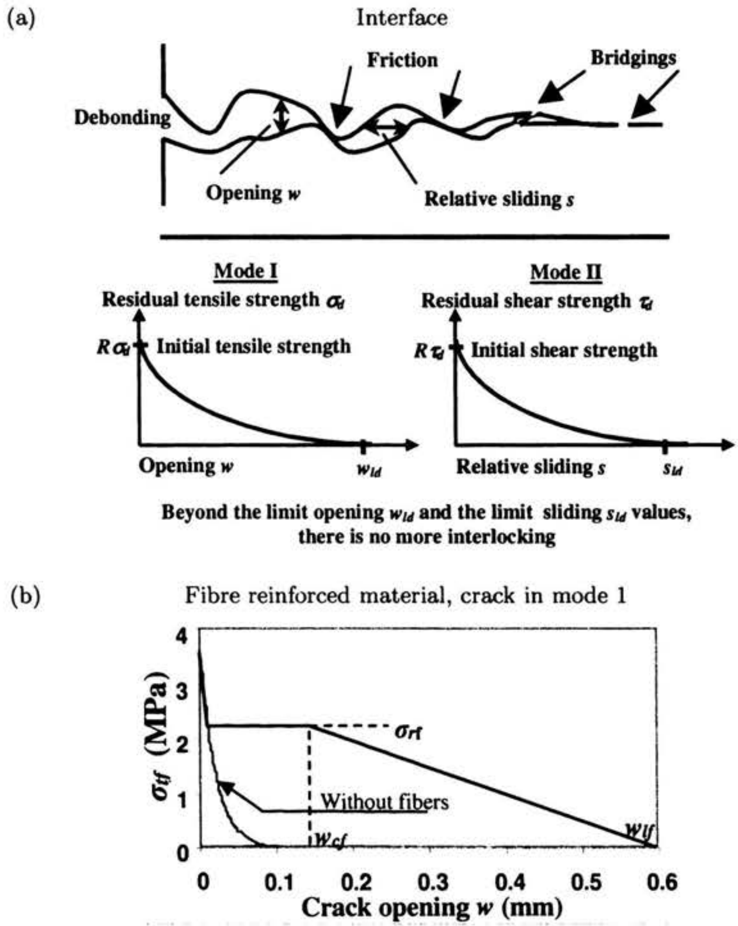


FIGURE 26. (a) Schematic representation of a debonding, the associated interlocking forces. (b) Interlocking forces in a fibre reinforced material, crack in mode 1.

However, even in the case of smooth interfaces, characterised by low values of w_{ld} and s_{ld} (the limit opening and limit sliding values beyond which there is no more interlocking), interlocking cannot be neglected. Even then, it has a major incidence.

9.2.2. Interlocking in mixed mode. Interlocking in mixed mode is not the addition of the closing forces obtained in pure mode 1 and pure mode 2. Actually, there is a strong interaction between the two modes. An opening w of the interface is likely to damage the shear interlocking capacity and conversely. Indeed, whatever the origin of the damage, it gradually results in the disruption, first of chemical, second of physical bonds between the two separated surfaces. Bonds broken in pure tension will necessarily at some point hamper the shear interlocking resistance, and the reverse is true.

Taking that into account, the following method is proposed. It is proposed on the modelling example of the tests performed in LMDC, Toulouse, on composite specimens with a steel substrate. The comparison of the calculated and experimental results validate the method (Fig. 29).

Computation

In this example, the relationship between the residual strengths and the interface opening or sliding was obtained from literature. For mode 1 propagation, a law from Hordijk [44] and simplified by Toumi [45] was used:

$$\sigma_d(w) = R\,\sigma_d\, e^{-5\,w/w_{ld}}$$

where $R\sigma_d$ is the initial tensile strength, w_{ld} is the opening range within which interlocking is effective. When $w = w_{ld}$, this simplified law ends in a non-zero but actually negligible value of σ_d.

The interlocking stress σ_d decrease recorded with the interface opening is an irreversible damage. Consequently, as a first rough approximation, it was assumed that closing and re-opening is given by the following linear law:

$$\sigma_d(w) = \sigma_d(w_{\max})\, w/w_{\max}$$

where $w_{\max}$ is the maximum relative opening previously reached.

For mode 2 propagation, it was assumed that the shear interlocking is governed by laws of the same type as in mode I. It follows that:

$$\tau_d(s) = R\,\tau_d\, e^{-5\,s/s_{ld}}$$

where $R\tau_d$ is the initial shear strength, s_{ld} is the relative sliding range within which interlocking is effective. The values of $R\sigma_d$, $R\tau_d$, w_{ld} and s_{ld} are specific to the considered interface.

The direct tensile and shear strengths measured on interface samples (see Sec. 6.1.1) were respectively $R\sigma_d = 0.5$ MPa and $R\tau_d = 1.3$ MPa. From the results reported by Hordijk and in regard with the actual roughness of the broken interface, the value of w_{ld} was assumed equal to 0.05 mm. In addition, it was assumed that $s_{ld} = w_{ld}$. The interlocking laws derived from these assumptions and taken into account in the simulations are presented in Fig. 27.

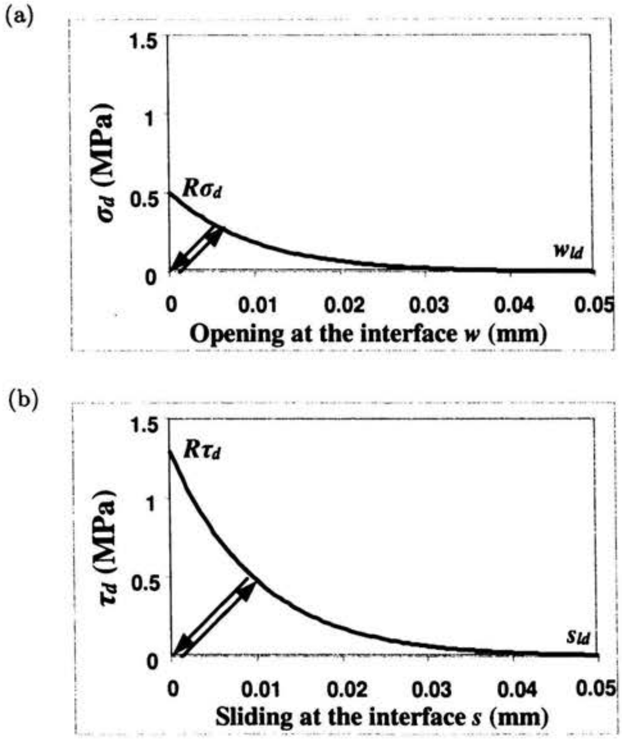


FIGURE 27. Interlocking at the base-overlay interface: (a) Interlocking law σ_d–w (mode 1), (b) Interlocking law τ_d–s (mode 2).

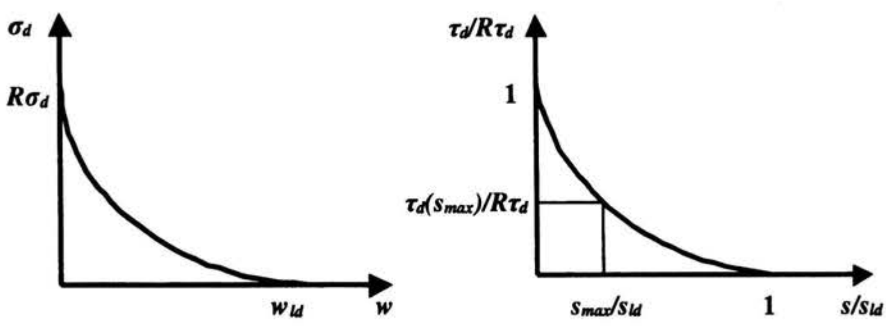


FIGURE 28. Interlocking at the base-overlay interface: management of the damage interaction between tension and shear, example of calculation in tension (mode 1).

To take into account the interaction between modes 1 and 2, and assuming that bonds broken in pure tension will necessarily, at some point, hamper the shear interlocking, and reciprocally, the following relationships are proposed:

$$\text{tensile interlocking}: \quad \sigma_d(w, s_{\max}) = \sigma_d(w)\,\frac{\tau_d(s_{\max})}{R\tau_d}\,,$$

$$\text{shear interlocking}: \quad \tau_d(s, w_{\max}) = \tau_d(s)\,\frac{\sigma_d(w_{\max})}{R\sigma_d}\,.$$

Such relationship is depicted in Fig. 28.

Validation by comparison with experiment

Two series of tests were considered, one representing the debonding from "mechanical origin" (flexure tests with the overlay on the tension side), the other one representing the debonding from "length changes origin" (overlay on a stretched substrate). In both cases, all the tests had in common the following features.

The overlays were made of fibre reinforced mortar.

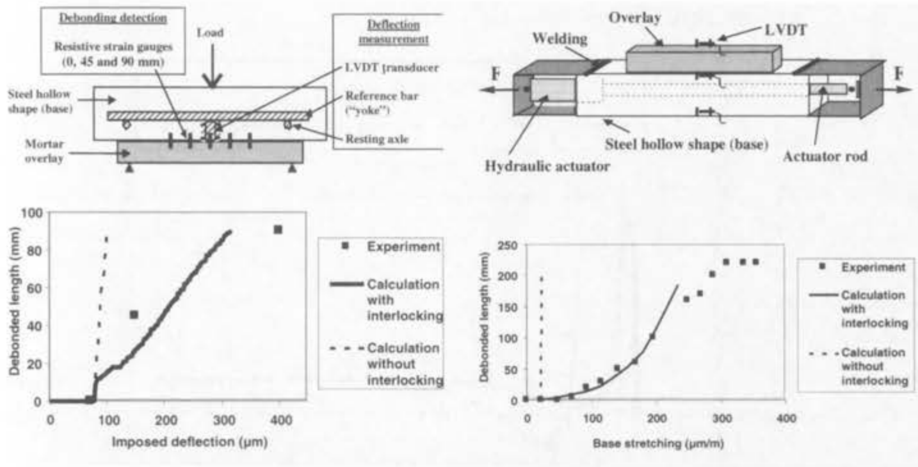
- A 20 mm thick layer was cast directly on the prepared steel base surface.
- The specimens were cured for 7 days before the tests.
- The reinforcing fibres were 30 mm long and 1.6 mm wide flexible fibres. These fibres, made of amorphous metal, are corrosion resistant, shaped like thin ribbons, approximately 30 μm thick, and are characterised by a very strong bond with cement-based matrices.
- The bond characteristics are those presented in the above computation.

The actual fibre reinforcement and tensile strength of the overlay, different in the two cases, was taken into account.

For each type of test, the comparison of experiment with computation is presented in Fig. 29. In the case of debonding of mechanical origin, the involved debonding length is the one measured on each side of the crack which initiated debonding, under the load. The result is then dependent on the fibre reinforcement of the overlay. In the case of the debonding from length changes origin, the involved debonded length is measured from each extremity of the overlay. As no fibre cross the end section of the overlay, this result is independent of the fibre reinforcement of the overlay.

Good agreement of the computation with the experiment confirms the validity of its fundamentals.

The dot lines show the result of calculation ignoring interlocking, in the crack and along the interface. The complete disagreement with experiment clearly evidences the major role of interlocking and the absolute need to take it into account.



Debonding of mechanical origin Debonding of length changes origin

FIGURE 29. Comparison of computation with experiment.

Taking into account the interaction of modes 1 and 2 in the actual interlocking is also essential. Calculations carried out ignoring them lead to unrealistic results.

10. Debonding propagation

Debonding propagation as it results from the modelling presented and validated in Sec. 9 can be followed step by step.

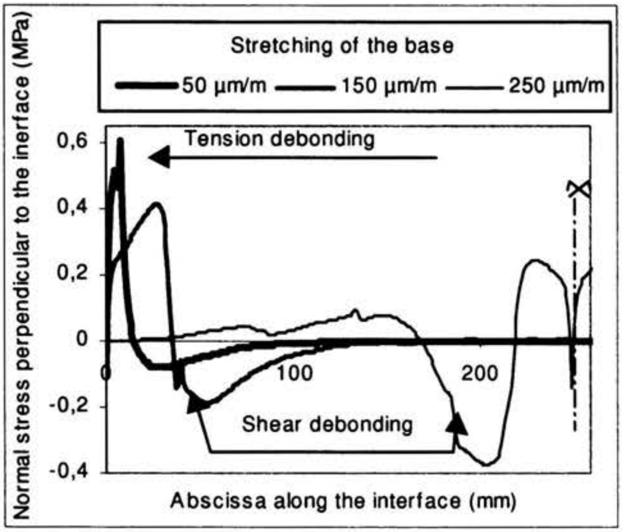
Down there is presented the example of the debonding of length changes origin such as it is computed in the case of the stretched substrate test. The calculating parameters are those of Sec. 9, with the assumption of a potential crack at mid-length of the specimen.

The result is illustrated in Fig. 30. It shows the evolution, with the abscissa and with the stretching of the substrate, of the normal stress σ_d perpendicular to the interface and of the shear stress τ_d at the interface.

In this case, one sees that:

- Debonding first propagates by tension failure of the bond. Then the tip of the debonded length is marked by a sharp peak of tensile stress. To contribute to the static equilibrium, this tensile peak is followed by a compression hump. In the meanwhile, the shear stress remains moderate. In Fig. 30, it is still the case for a stretching of $50\,\mu$m/m.
- After debonding along a given length, short in the case of the above example, propagation continues by shear failure. The debonding tip is

(a) Normal stresses



(b) Shear stresses

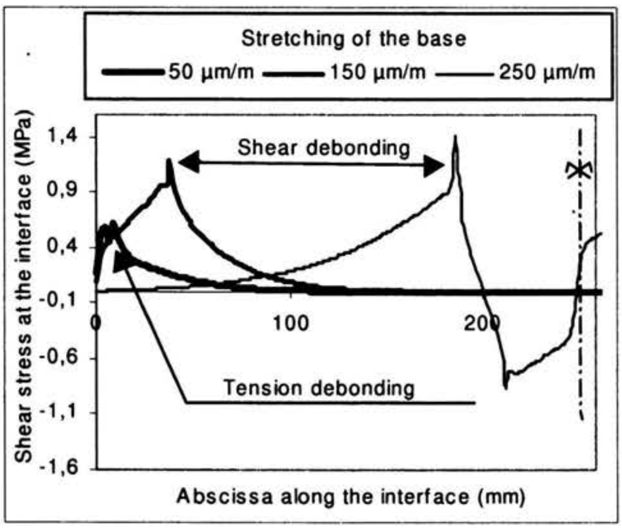


FIGURE 30. Normal and shear stresses calculated along the interface for three different values of the base stretching (because of the symmetry, only one half of the domain is represented).

located by a sharp peak of the shear stress. This change of propagation mode is the consequence of interlocking. Due to it the debonded area of the interface continues to carry tensile forces.

- Because of interlocking, the normal tensile stress σ_d doesn't drop to zero immediately after debonding. Actually, a significant hump of tensile interlocking stress remains which, along the debonded zone, is enough to equilibrate more than the forces acting to open the interface, placing then the tip of the debonding in the compression hump. Under this condition, a tension failure turns impossible and debonding then propagates by shear failure.
- When the stretching of the base increases, a crack opens at mid-length of the overlay and a similar phenomenon is initiated from the crack.

The debonded length at which propagation changes from tension to shear failure is of course sensitive to the interlocking parameters. It is expected to shorten when the interface roughness increases.

Calculations in the case of debonding of mechanical origin indicate that tensile failure remains prominent much longer, sometimes during the whole debonding process. That is easily explained by the trend of the cracked overlay not to follow the curvature of the substrate (see Fig. 14(a)). It induces additional tension forces perpendicular to the interface which come in addition to the ones calculated with no curvature.

The trend of the overlay to curl acts in the same way.

11. Effect of a reinforcement of the overlay. "First monotone straining" or "shrinkage and fatigue" tests?

In the case of a thick overlay, usually in the case of bridge deck repair, the overlay can be reinforced by a steel bars system. In the other cases, repair of slabs on soil or concrete pavements, spread concrete repairs, the reinforcement is provided by fibres.

This Section focuses on fibre reinforcements. The bar reinforcements act in the same way (Beranard [46], Gagné *et al.* [47]).

The laboratory tests and *in situ* experience clearly show a positive effect of a fibre reinforcement. This Section will put in light and explain the differences between the findings resulting from a "first monotone straining" or from "shrinkage plus fatigue straining".

One of the first attempt of fibre reinforced bonded overlay was made in Greene County, USA, (Betterton *et al.* [48]), to repair concrete road pavements. It enlightened the beneficial effect of a steel fibre reinforcement of the overlay on the durability of the repair.

The fibres used were common steel wire fibres. Their dosage initially chosen was very high, $90\,\mathrm{kg/m^3}$. Other results obtained by various authors confirmed the positive effect of a metal fibre reinforcement of the overlay even at much lower dosage, from 25 to 40 kg/m^3. They also demonstrated that, at usual dosages, the fibre reinforcement of the overlay is not enough to prevent crack reflection from the substrate (Verhoeven [49]). A well documented example is the case of the Motorway 40 in Montreal, Canada, presented in Sec. 8.2.2. Although a small amount of fibres added to the overlay, 22 to 34 kg/m^3, a significant benefit was observed.

11.1. Types of fibres

The experiments and calculations demonstrated that, to efficiently prevent or limit debonding it is necessary to act as soon as the thinnest crack openings. Low modulus fibres, needing a non-negligible crack opening to provide a significant force, cannot match this requirement. Among the commonly used fibres, only the metal ones are convenient at low or medium dosages.

The metal fibres are classified in two families: "slipping fibres" and "high bond fibres". The typical post-crack behaviour of each of them and the parameters used to quantify it are illustrated in Fig. 31

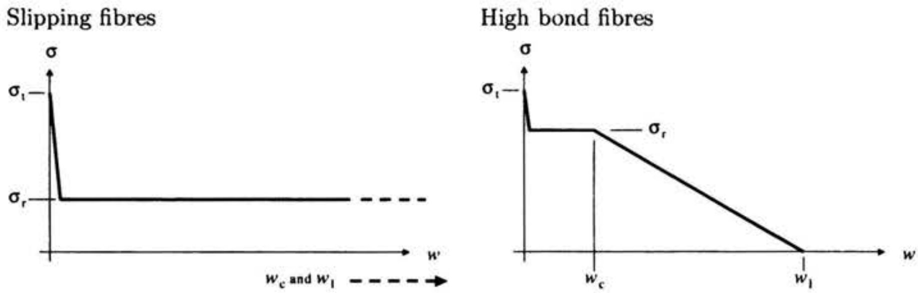


FIGURE 31. Typical post-crack behaviour of "slipping fibres" and of "high bond fibres" at equal volume content of fibres; definition of σ_t, σ_r, w_c, w_l.

When a crack opens, the "slipping fibres" slip and never break. They provide a low but very long plateau of post-crack residual strength. A typical example is the hooked end steel fibres.

The "high bond fibres", characterised by a very high bond with the concrete matrix, provide a high but short post-crack strength plateau. Afterwards, these non-slipping fibres begin to break and the residual strength decreases.

At equal volume, high bond fibres provide a σ_r plateau strength about twice the one of slipping fibres. But this σ_r strength is available only within thin crack openings, sometimes less than 0.2 mm.

The laboratory tests reported down there compare 30 mm long fibres. The slipping ones are steel hooked fibres. The high bond ones are amorphous metal fibres. These are like thin shining ribbons, about 30 μm thick and 1.6 mm wide. They are totally stain proof . Their very high bond with the cement matrix is the result of their high specific area.

11.2. Case of a "first monotone straining"

It is the case of many laboratory tests and the case of practically all the characterising tests.

11.2.1. Laboratory tests. Typical results are those, numerous, performed in LMDC, Toulouse, since 1993 in flexure with the overlay on the tension side [50, 35]. The test fitting and an example of result were presented in Sec. 8.2.1 and Fig. 18.

As long as there is no debonding, the devices spanning the interface measure a compression. Debonding makes their signal turn towards tension. Then, in Fig. 18(b), propagation is characterised by the rightwards moves of the plot.

- Without fibre, debonding occurs at the same deflection as the first crack and instantly propagates over all the investigated length along the interface.
- With the fibre reinforcement considered here, the first crack initiated debonding but there was no propagation. A second crack, which opened in the vicinity of LVDT 2, brought an other debonding initiation at this location, but still with no significant sign of propagation.

Obviously, the fibre reinforcement of the overlay has a beneficial effect.

In these tests, 35 kg/m^3 of high bond fibres were necessary to significantly delay debonding. For the same result, 80 kg/m^3 of slipping fibres were necessary.

The full scale test campaign carried out in Zmigrod, Poland, confirmed influence of dispersed fibre reinforcement on overlay cracking and delamination.

11.2.2. Modelling findings. On the bases presented in the Sec. 10, calculation was applied to the modelling of the flexure test for debonding of mechanical origin of Sec. 11.2.1 (Sabathier [43]). The cases of a plain mortar overlay and of one reinforced with 35 kg/m^3 of high bond fibres were then compared. The influence of an initial bond defect centred on the potential crack of the overlay was also investigated, two defect length were considered: 40 mm and 80 mm.

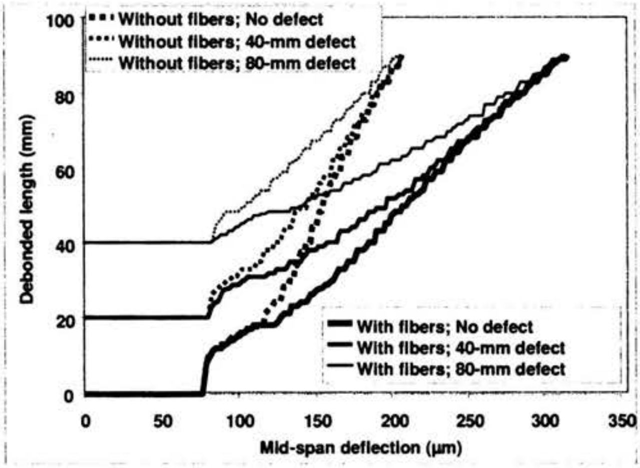


FIGURE 32. Debonded on length each side of the center crack as a function of the mid-span deflection (overlay with and without fibers, 40 mm and 80 mm defects).

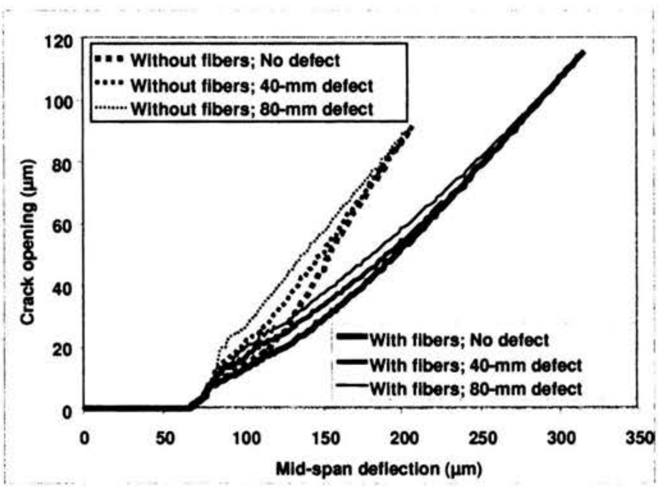


FIGURE 33. Crack opening versus the mid-span deflection (overlay with and without fibers, 40 mm and 80 mm defects).

The results confirm and deepen the findings of laboratory tests. They are presented in Figs. 32 and 33.

- The beneficial effect of the fibre reinforcement is clearly evidenced. It significantly slows down the speed of debonding propagation.

Within the investigated domain, until 160 mm of debonding propagation (80 mm each side of the crack), the crack opening remains less than 120 μm. It confirms that, to be effective, prevention or limitation of debonding must act in the domain of the thinnest crack openings. It is the domain where the high bond fibres provide their maximum efficiency.

It is disappointing to note that, at equal debonded length, the crack opening calculated in the case of the fibre reinforced overlay is larger than the one calculated with the unreinforced overlay. It is easily explained when one notes that, at equal debonded length, the fibre reinforced sample withstands almost double imposed mid-span deflection. In other words, at equal deflection the crack opening in the fibre reinforced overlay is almost twice lower than in the plain mortar overlay.

- A fibre reinforcement cannot hide a bond defect, but, after a given length of debonding propagation, the initial defect is no longer visible.

Another result is that, in these conditions of a "first monotone straining", the fibre reinforcement considered here, equivalent to about 80 kg/m^3 of usual steel fibres, has only very small effect to slow down the crack propagation through the depth of the overlay.

In a totally independent work, a modelling by Bernard [46] dealing with the case of length change (shrinkage) of the overlay in a "first monotone straining" arrive at the same conclusion: in these conditions, 80 kg/m^3 of steel hooked fibres is the minimum necessary to note an effect on the speed of crack propagation through the overlay.

11.3. 11.3 Case of "shrinkage plus fatigue"

In situ structures are submitted to complex and essentially unsteady actions. It is quite different from the case of a "first monotone loading". The following results enlighten the effect of this difference on the response of the structure.

11.3.1. *In situ* findings: Montreal Motorway repair. This repair work is presented in Sec. 8.2.2.

On a concrete Motorway with a traffic of 30 000 vehicles per day, several repair system were compared: plain concrete overlay, fibre reinforced overlays with 22 to 34 kg/m^3 of conventional metal fibres. Also, connecting the overlay to the substrate by nails previously gun driven inside the latter was investigated. Among the three lanes of the pavement, each one received a different amount of nails: no nail, one nail each 30 cm, one nail each 45 cm.

The results are summarized as follows:

- In plain concrete overlays, cracks developed at an accelerating rate. Within two years the repair was out of order.
- In the fibre reinforced overlays:
  - cracks developed at a slower rate than without fibres to reach a steady state at the end of the first year; after 12 years of use these repairs were still sound with no or negligible detected debonding;
  - the involved cracks remained thin and a coring campaign performed after three years of use indicated that most of them developed only on about the half-height of the overlay.
- No significant difference was visible between nailed and not nailed lanes.

Figure 34 illustrates these points.

Influence of the fibre reinforcement

Influence of the dowelling by gun driven nails

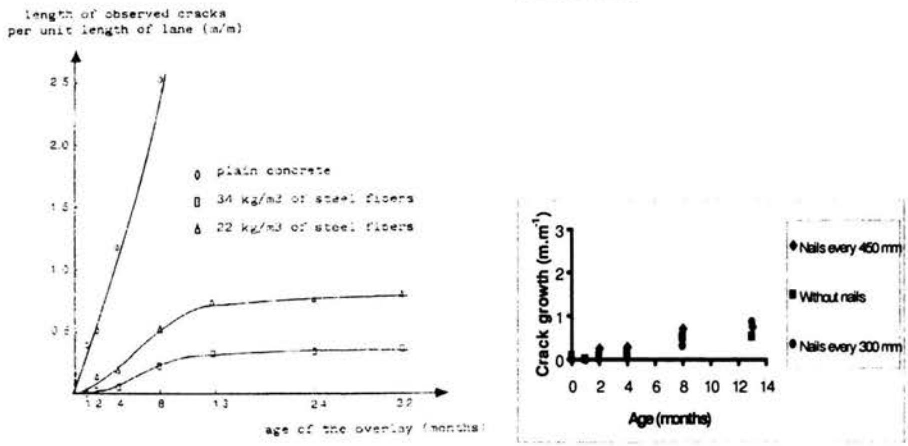


FIGURE 34. Experimental repair of Montreal Motorway 40: crack growth.

By comparison with the case of "first monotone straining", two points must be outlined:

1. 22 to 34 kg/m^3 of conventional metal fibres are fully efficient, compared to a minimum of 80 kg/m^3 necessary in the case of a "first monotone straining".
2. The cracks propagation through the overlay was stopped at about mid-height of the overlay. On the contrary, during a "first monotone straining", calculations indicate that a crack quickly reaches the interface and that fibres have only a slight effect to slow its propagation.

That shows a fundamental difference in the response of a repaired structure to a "first monotone straining" or to *in situ* conditions.

In situ overlays withstand shrinkage straining, fatigue and not uniformly increased loading which induce earlier cracking at much lower curvature level than in the above laboratory tests. Then, at lower curvature, lower forces are needed to restrain crack opening and lower fibre reinforcements can have a significant effect. Moreover, the concrete interlocking of such earlier cracked structures is damaged by fatigue loading. On the contrary, the bridging forces provided by a fibre reinforcement are much less affected by fatigue. It is then expected that, in case of fatigue loading, the effect of fibres turns more visible because of the vanishing of the part of the bridging forces coming from the cement matrix interlocking.

From these considerations, it becomes evident that, if "first monotone straining" tests and calculations are totally reliable to investigate the mechanisms involved in debonding; on the contrary they are not convenient to predict *in situ* behaviour.

A new type of investigation must be started: in "shrinkage and fatigue" conditions. It includes cracking at lower curvature, helped by shrinkage effects, and fatigue damaging of the interlockings, along the propagating cracks in the overlay and along the debonding interface.

11.3.2. "Shrinkage and fatigue" type laboratory tests. A campaign of laboratory tests built on the same bases as those of Sec. 8.2.1 for debonding of mechanical origin was developed to fit the "shrinkage and fatigue" requirements (Turatsinze *et al.* [51, 52]). The results, in good agreement with the *in situ* findings, confirm the above argument.

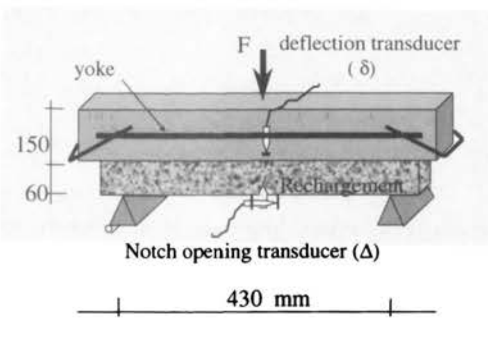


FIGURE 35. "Shrinkage and fatigue" tests: experimental fitting.

Experiments

A notch was managed in the overlay when casting to create a weak line where shrinkage would initiate a crack in the overlay before the time of testing (at the 7^{th} day). Moreover, the notch located the crack, making possible to fit a LVDT sensor to monitor its width.

The experimental fitting is sketched in Fig. 35. The metal bases were 150 mm high, the overlay 60 mm thick and the notch 20 mm deep. At the time of test (7 days) a spontaneous crack, about 5 mm long, was visible. Three types of mortar overlays were investigated:

M0: without fibre, $\sigma_t = 3.5\,\text{MPa}$,

M1: with $40\,\text{kg/m}^3$ of hooked steel fibres 30 mm long, $\sigma_t = 3.4\,\text{MPa}$, $\sigma_r = 1.3\,\text{MPa}$, $w_c = w_l =$ several mm,

M2: with $20\,\text{kg/m}^3$ of high bond fibres 30 mm long, $\sigma_t = 3.4\,\text{MPa}$, $\sigma_r = 1.6\,\text{MPa}$, $w_c = 0.2\,\text{mm}$, $w_l = 1\,\text{mm}$.

According to the "shrinkage and fatigue" type of the test, usual amount of fibres was expected to provide significant effect.

A fatigue loading was applied. It was a 5 Hz sinusoidal loading between a quasi-zero load (0.1 kN) and the load (10 kN) necessary to, in a first monotone loading without drying shrinkage (overlay sealed), initiate cracking at the tip of the notch.

Results

They confirm that, in these conditions, a medium fibre content (of the order of those used in the Montreal repair and twice less than which is necessary in a "first monotone straining") can provide a significant benefit.

Figure 36 presents the debonding propagation on each side of the initiating point (the crack in the overlay). The delay of debonding propagation provided by the fibre reinforcement is evident. One notes again that, in a matter of debonding delaying, 20 kg/m^3 of high bond fibres are more efficient than $40\,\text{kg/m}^3$ of usual steel fibres.

Figure 37 reports the propagation of the crack through the overlay. On the contrary of the "first monotone straining" case and in accordance with the *in situ* observation on Montreal Motorway, when fibres are present the crack propagates progressively towards the interface. In the plain mortar overlay, the propagation is practically instantaneous. With $40\,\text{kg/m}^3$ of hooked steel fibres, 60 000 cycles were necessary to reach the interface. With $20\,\text{kg/m}^3$ of high bond fibres, 120 000 cycles were necessary.

A stabilisation of the crack propagation about at mid-height of the overlay was not observed as in Montreal Motorway. This difference may be due to a

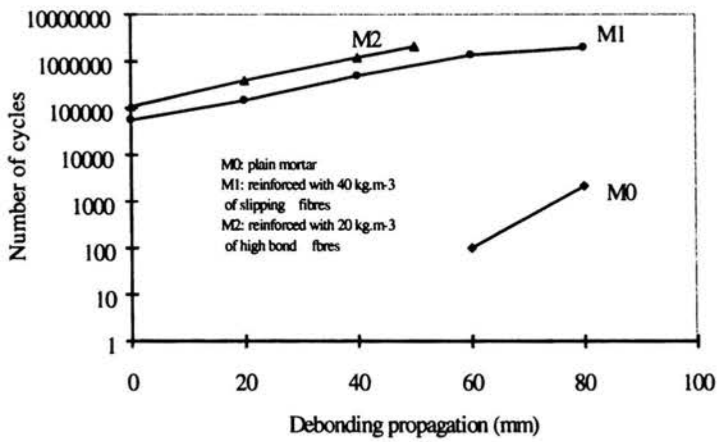


FIGURE 36. "Shrinkage and fatigue" tests: debonding propagation on each side of the initiating point, influence of the fibre reinforcements.

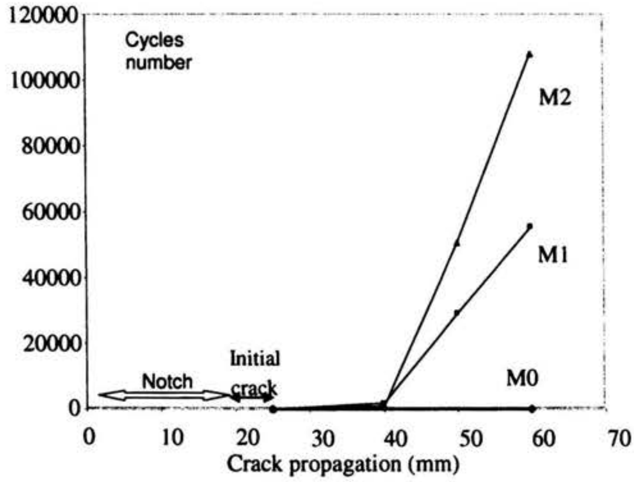


FIGURE 37. "Shrinkage and fatigue" tests: crack propagation through the depth of the overlay versus the number of cycles.

different balance between shrinkage and bending in the laboratory tests and *in situ* in Montreal. With a 7-day drying shrinkage in the laboratory, this one was surely less than *in situ* in Montreal.

The maximum crack opening at the end of the test, illustrated in Fig. 38, is wider than in the case of a "first monotone straining", but it remains limited in the domain of efficiency of high bond fibres.

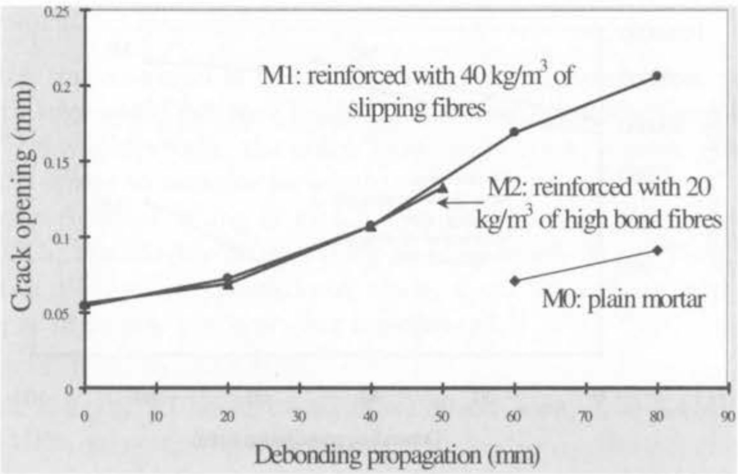


FIGURE 38. "Shrinkage and fatigue" tests: crack openings, influence of fibre reinforcements.

The results of this series of tests clearly evidence two essential points:

1. *the interest and the need to consider the conditions "shrinkage and fatigue" for tests representative of the actual* in situ *conditions,*
2. *in a perspective of modelling, the need of further researches to investigate the damaging of interlocking under fatigue loading, in cracks and along debonding interfaces.*

12. Fatigue

Very little is known about the fatigue of a debonding interface and more investigations are necessary.

Attention must be paid to the evolution of the interlocking in the two modes, 1 and 2, and their interactions. Also, the knowledge of the evolution of the behaviour in fatigue of a fibre reinforced crack must be deepened.

Available results (Silfwerbrand [23]) indicate that, before initiation of debonding, fatigue loading of an overlaid structure has no harmful effect.

13. Conclusion and recommendations for durable repairs

The problem of thin bonded overlays is their cracking and debonding.

Presently, simple design codes for durable repairs are not yet available. Calculation must be carried out via finite elements modelling. They provide interesting results but data on the interlocking parameters at the interface and their evolution in fatigue loading are still lacking.

To delay or prevent debonding, one must consider the following points:

- Enhance the bond strength at the overlay-substrate interface, especially by a good preparation, including a thorough cleaning, of the substrate surface. As far as possible, the use of jack hammer must be avoided.
- Decrease the length changes mismatching, especially by decreasing the shrinkage of the overlay and by a pre-soaking of the substrate.
- Restrain cracks opening, usually by a fibre reinforcement of the overlay. In this regard, high modulus and high bond fibres are the most efficient.

Recommendations for a durable repair of bridge deck

- Remove the loose or polluted material (from 5 to about 10 cm depending on the case) by water jetting. It is the most efficient substrate surface preparation. It removes selectively the loosest materials, it is harmless for the eventual steel reinforcements and it provides a high roughness surface and sound surface. It is expensive, but in regard with the price of a bridge, it is worthwhile.
- Flush the surface with pressure water immediately after water jetting and again immediately before pouring the overlay.
- Water jetting and the two flushing have saturated the substrate and make it swell. The future unswelling will limit the length mismatching induced by the shrinkage of the overlay.
- Don't use bonding agent. Let dry the substrate in surface and pour the overlay. Water pockets at the surface of the substrate must be strictly avoided.
- Fibres or steel bars are advised as reinforcement of the overlay.
- Ensure a good cure of the overlay and protect it from evaporation until it is covered by the waterproofing layer, if there is, and the asphalt based wearing layer. In these conditions, the shrinkage of the overlay is limited to its endogenous component.

Recommendations for a durable repair of slab on soil or pavement

Large areas must be treated and generally a uniform depth of the substrate is to be removed.

- Remove the loose or polluted material (generally a few centimetres deep) by scarification. The obtained surface is rough with very few microcracks. If there are pot-holes, fill them with concrete, level and roughen their surface and let harden. Before overlaying, take care to take off the loose upper layer of this preliminary repair.

- Flush carefully with high pressure water. It will clean the surface and pull off the sapling material if there is. Wash again immediately before pouring the overlay.
- Make sure that the substrate was saturated enough by the previous washings, if not, soak it.
- Don't use bonding agent. Pour the overlay on the substrate dry in surface, absolutely avoid water pockets.
- Reinforcement of the overlay is highly recommended, high bond metal fibres are the most efficient.
- Curing? A good cure is the usual recommendation. In the author's opinion:
  - A good cure delays drying shrinkage and have as consequence to make it develop in a stronger and stiffer material, inducing higher curling debonding stresses and larger corner lifting.
  - A light cure, just enough to prevent plastic shrinkage cracking, results in a drying shrinkage beginning as the material still has a low stiffness and a large creep and relaxation capacity. Then the built in stresses are lower and a larger portion can vanish by creep and relaxation. If some early cracks occur, controlled by the fibre reinforcement they should remain very thin, moreover they act to provide a supplementary effect of stress release.
- Joints:
  - They must be limited to 1/4 or 1/3 of the overlay thickness.
  - As far as possible they must match the joints of the substrate.

Recommendations for a durable strengthening or lining of a sound surface structure

The same as for a slab on grade or pavement repair, but the surface scarification is replaced by sand blasting.

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