Rehabilitation of Bridges with Concrete Overlays

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ABSTRACT: The increasing demand of repairs and strengthening of existing structures requires economic and practical new building methods. Growth in both traffic volume as well as load increases due to for example the expansion of the cross-border trade combined with wear from the boom in construction activities has led to this. In lieu of a complete replacement of an existing structure it may prove a politically lucrative option to improve and strengthen such a structure by adding new structural components. Therefore, the application where new load bearing concrete layers are added takes on a new meaning. For such retrofitting projects the Hilti Corporation has developed a special injection-type connector to attach new structural concrete layers to existing concrete structures. Static and dynamic research, including a fatigue approach as required in bridge construction, form the experimental basis for a comprehensive design concept.

1. STRENGTHENING AND RETROFITTING WITH CONCRETE OVERLAYS

1.1 Reasons for overlays

During the last decades various preservation-, strengthening- and repair methods of reinforced concrete structures have experienced growing popularity and gained ever more significance. Typically structural elements require strengthening in order to permanently increase the load-bearing capacity, improving the serviceability and/or the durability as well as the fatigue behaviour of slabs, beams, columns and stiffening elements. There are many reasons for such measures originating from the change of use, change of the static system, reinforcement corrosion damages, new design codes inducing higher service loads and/or new design regulations, unusual loads (e.g. impact, explosion, fire, and earthquake) as well as planning, design and even construction execution errors. With respect to cost efficiency, but also for political reasons it might be necessary to rather retrofit an existing structure by the placement of concrete overlays instead of replacing the entire structure. Therefore, the application of new structurally load bearing concrete layers (Fig. 1) takes on a special meaning. By these means the effective member depth and thus the flexural resistance of the cross section can be increased. While tensile forces can be transferred by appropriate reinforcing elements (rebars), the shear transfer needs special attention, as it depends on the interaction of the connecting elements and the condition of the concrete to concrete interface.

1.2 Composite structure

If a new layer of concrete is applied to an existing concrete structure with the aim of strengthening or repair, reference is made to a composite concrete structure (Fig. 2). The overlay is usually cast directly or placed as shotcrete. It functions to increase the flexural compression or flexural tension zones, depending on the placement. In general, the structural characteristics of the strengthened structure are similar to those of a monolithic structure. If structural elements made of reinforced and/or pre-stressed concrete are post-strengthened by concrete overlays (joints parallel to the system’s neutral axis), the entire cross section can be regarded as cast in one for the determination of the ultimate load capacity. Therefore it must be verified that the internal shear capacity between the existing and new concrete will be able to resist the loads at the ultimate limit state.

Figure 1. Strengthening of bridges by means of concrete overlays
1.3 Composite structure

For the realisation of a good bonding the surface of the existing concrete construction has to be prepared with suitable procedures. Practical experiences as well as theoretical models show that differential shrinkage and frequent variations in temperature gradients over the cross sections are the main causes for a possible separation of the two concrete layers. Research work (Randl 1997, Tschegg, Inguber, Surberg & Münger 2000) investigated two parameters, namely the influence of the surface preparation with respect to the effectiveness of the bond and whether mechanical connections crossing the interface are required. Recent research confirms that high shrinkage with small mechanical interlocking and increasing aging can lead to a decrease of the long-term bond strength (Beushausen, Dehn & Alexander 2005). Shrinkage of the new concrete overlay can be reduced by a careful selection of the concrete mix.

In the new concrete overlay stresses resulting from shrinkage and differential temperature gradients typically reach their maximum at the perimeter and local concentrated tensile forces (so called peeling forces) perpendicular to the interface may develop. The combination of external and internal stresses often exceeds the capacity of the initial bond. Furthermore, these stresses are time dependent, and bond failure can take place years after overlay placement. Therefore, in many cases it is necessary to position reinforcement or connectors across the interface (Fig. 3).

2. SHEAR CONNECTORS FOR CONCRETE OVERLAYS

2.1 Perimeter and field

At the perimeter of a new concrete layer the concrete dries out, contracts producing tensile forces and delamination perpendicular to the interface, eventually cracking the concrete. In order to counteract this process, connectors have to be installed all along the perimeter. In the field of the concrete overlay shear connectors are required if the shear load in the interface under consideration can not be resisted by the interlocking effect of the roughened joint surface alone.

With the relatively recent method of reinforcing bridges with concrete overlays opinions of design philosophies diverge: A thorough roughening of the existing concrete with high-pressure water jets might be sufficient to resist the shear or transverse force in the bond with the new concrete. A dowelling of existing and new concrete would not be necessary to prevent that the two layers shift relative to each other when they are loaded by a shear force. Research confirms this hypothesis for normal impact in a carriageway slab based on surface conditions prepared in a laboratory environment. However, one should also consider instances when oil from a compressor spills or a dust layer develops making the roughened concrete unclean. The bond at the contaminated area would no longer be sufficient to transfer the shear load in the interface between existing and new concrete. For such practical conditions - in everyday life where perfect and controllable laboratory conditions do not exist - the other opinion favouring dowelling of the existing concrete with the new concrete overlay, makes its presence. Therefore, during the laboratory tests for the system described in this article, the adhesion of the interface between the new and old concrete was minimized by applying oil, normally used for formwork, before casting the concrete overlay.

2.2 Concrete connectors

The simplest form of a shear connector is a straight rebar. The disadvantage of this solution is the required minimum embedment depth of 9 - 10 times the rebar diameter (Randl & Wicke 2000). This results in concrete overlay thicknesses which might be greater than the minimum thickness necessary for load requirements, simply because the minimum concrete cover has to be added to the embedment depth. Therefore, bent or hooked rebars are used in practice. In order to avoid concrete crushing when using minimum values of mandrel diameters, cross bars inside the bends are required, this is however cumbersome to
construct due to alignment issues. Alternate solutions exist like welded heads or threaded rods with screwed plates (Fig. 4 types a) and b)). In the latter case the connection of the plate to the threaded rod is to be assured either by adhesion or by means of a lock nut, in addition, the plate must exhibit a sufficient area and rigidity (Furche 1994).

Recently a new trumpet shaped hollow shear connector (the so called “HCC-B” element) made out of malleable cast steel was developed by the Hilti Corporation (Figs 4c, 5). This new innovative product exhibits several advantages compared to the alternatives specified so far. Contrary to the other systems the shear connector is driven into a pre-drilled hole using a hammer drill prior to injection with Hilti HIT-RE 500 mortar. Specially designed ribs at the external side of the hollow shaft ensure a proper installation even under construction site conditions. The ribs develop a rigid friction hold to the borehole, thereby allowing limited immediate loading (1.00 kN) already before mortar injection. The shear connector Hilti HCC-B (Fig. 5), measuring 180 millimetres in overall length, can be installed to a depth varying from 90 to 125 millimetres and must project a minimum 55 millimetres in the new concrete overlay (Hilti Fastening Technology Manual 2005). Therefore the Hilti HCC-B is particularly suitable for applications where the thickness of concrete overlay is limited. Its ribbed surface provides a rigid connection with the adhesive mortar which is injected through two holes at the end of the hollow shaft after setting the connector, ensuring an even mortar distribution in the hole.

3. EXPERIMENTAL BACKGROUND AND SYSTEM EVALUATION

3.1 Mechanism

The first comprehensive shear tests investigating the load bearing behaviour of interfaces roughened with modern equipment, in combination with post-installed connectors crossing the joint, were conducted in 1995-1997 (Randl 1997). The connectors used in these tests were standard reinforcement bars, partly provided with welded heads (Fig. 4 type a)). The results of these tests have been presented in (Randl 2004). A debonding agent was used to account for potentially unclean surfaces typically found on jobsites, which would result in a reduction of the chemical adhesion. The main conclusions can be summarized as follows: During the tests it was observed that rough joints loaded in shear produce a “dowel effect” in the shear connector due to the bending shear force. Simultaneously a “tensile force” is developed resulting from the delamination along the joint between the two surfaces. At the same time the tensile clamping force is equilibrated by a compression component producing friction along the joint between the two concrete layers (“saw tooth” model (Randl, Münger & Wicke 2005)).
From these observations, it can be concluded that a rough surface transfers the shear force predominantly via the mechanism "friction" and a smooth joint surface via the mechanism "dowel action". A third mechanism "interlocking" (i.e. keying effects) plays an important role in shear transmission, particularly for rough joints in combination with lower shear stresses requiring smaller reinforcement ratios across the interface. This is particularly evident with irregular roughness produced by high-pressure water jets. Tests have shown that keying effects in context with irregular roughness may even contribute to overall resistance after several tenths of [mm] displacement (Randl 1997). With a rough interface the shear connectors are loaded by a been-ding moment and a tensile load simultaneously. Due to this interaction only about 50% of the tensile yield stress may be developed in the cross section under the combined loading.

With reinforcement bars (Randl 2004), i.e. a concrete prism was loaded in shear acting parallel to the roughened base slab along the axis of the interface (Fig. 6). Static tests as well as dynamic tests under cyclic loading (Fig. 7) have been performed. The same test setup was used for both static and dynamic loading. Previous investigations with different setups have shown that the overall stress distribution in the shear interface may be influenced by the specimen-geometry and is also dependent on how the load is introduced into the test member (Randl, Münger & Wicke 2005). The shear tests confirmed the existence of the three resisting components being cohesion, friction and dowel action and verified the formerly obtained results (Randl 2004) conducted with post-installed rebars. In addition, tension tests and installation tests had been conducted with the new connectors.

The main difference between the shear connectors like the hollow cross-sectioned HCC-B element and a full cross section element such as a rebar is that the plastic usability under tension (normal force N) decreases to approximately 40% for the HCC-B element compared to 50% observed for rebars when subject to sliding and associated widening of the joint surfaces. This is due to the material concentration at the perimeter of the hollow element (HCC-B). This phenomenon could be verified by theoretical calculations (Fig. 8) as well as in the results of strain measurements inside the tubes of the HCC-B element. On the other hand, the dowel resistance (resistance to bending moment M) of the hollow shear connector can be increased compared with the full cross section due to the favourable cross-sectional shape for bending by approximately 20% (Hilti Fastening Technology Manual 2005). Dynamic testing confirmed that the malleable cast iron used to manufacture the HCC-B connector exhibits sufficient ductility to guarantee that the shear resistance after 2 million load cycles is not less

3.2 Further development

Follow-up tests with another type of connector, the earlier described Hilti HCC-B elements (Fig. 5), have been conducted. The test setup and test conditions were comparable to the previous tests.
than 40% of the static load bearing capacity, similar to standard ductile rebar elements (Randl, Münger & Wicke 2005). Tests with different steel ratios, thus varying the contribution of the three resistance components, verified that an overall reduction factor of 40% can be equally applied to all three contributors. This assumption is appropriate for a general engineering design of the resistance under fatigue loading.

4. DESIGN OF INTERFACE

4.1 Basic design

Based on the tests with cast-in reinforcing bars a basic design method was derived. This basic design approach is applicable for different interface roughness and reinforcement ratios and accounts for realistic site conditions concerning bond. The tests with the new Hilti Concrete Connector (HCC-B) confirmed this basic design approach. The detailed design procedure recommended for the HCC-B hollow element is given in (Hilti Fastening Technology Manual 2005) and is particularly suited for slab-like construction loaded by a bending moment, applications typically found in bridge construction and in building construction. If a bending moment acts on the structure (Figs 9-10), the concrete overlay is suitable for the concrete compression zone (strengthening of compression zone) and with the installation of a suitable reinforcement also for the tensile forces (strengthening of tension zone). The magnitude of the shear flow acting on the interface has to be calculated by the engineer.

4.2 Design shear strength at the interface

The general design approach as presented in (Randl 2004) considers all three mechanisms: cohesion, friction and shear resistance of the shear reinforcement (dowel action) positioned across the interface. The design shear strength of the interface, $\tau_{rdj}$, can be calculated by a single equation for different surface treatments Equation 1. An upper limit is given by the design strength of the concrete struts. With increasing surface roughness, shear resistance and shear stiffness are significantly improved.

$$\tau_{rdj} = \frac{\tau_{pdj}}{\mu} + \frac{\tau_{fdj}}{\mu_{fdj}} + \frac{\tau_{kjdj}}{\mu_{kjdj}} \leq \beta \frac{f_k}{y_k}$$  \hspace{1cm} (1)

The different components of Equation 1 are shown graphically in Figure. 11. Values for the different parameters have been listed for post-installed rebars in (Randl 2004) and can be obtained as per (Hilti Fastening Technology Manual 2005) for the Hilti HCC-B connectors. The constants $\kappa$ and $\alpha$ take into account the interaction between the tension force and the bending moment in the connector itself; $\kappa$ is limited to 50% or less depending on the shape of the cross section. Interlocking can act in conjunction with friction and dowel action only for irregular roughness like water jetted surfaces where significant keying effects are present.

![Figure 11. Set-up of design model.](image)

![Figure 12. Fatigue design recommendation.](image)

The recommended fatigue proof (Fig. 12) matches the design procedure for predominantly static loads ($V_{rd} = \tau_{rdj}b_j$). The proposed design format...
is adjusted to the Euro code 2 approach (Euro code 2 2001) and the DIN Technical Reports 101 and 102 (DIN Fachbericht 101 2003, DIN Fachbericht 102 2003), which regulate the construction of bridges.

4.3 Shear force at the perimeter

Special attention must be given to the design of the required steel cross section at the perimeter of the concrete overlay in order to avoid peeling of the concrete at the edges, induced by differential shrinkage or a temperature gradient over the height of the cross section. In lieu of a comprehensive detailed analysis of the stress distribution, one may for simplicity use for design (at a minimum) the cracking force $F_{cr}$ of the new concrete layer to be transferred. The cracking force $F_{cr}$ is resulting in a shear flow as expressed in Equation 2.

$$v_{ed} = \frac{t_n \cdot b_j \cdot k \cdot f_{ct,eff}}{l_e} \left[ \frac{kN}{m} \right]$$

With $t_n$ = thickness of the new concrete layer; $b_j$ = width of the structure considered (usually 1m); $k$ = factor to take into account the non linear distribution of internal stresses ($k = 0.8$ for $t_n < 300$ mm); $f_{ct,eff}$ = effective tensile strength of the concrete at the time of appearance of the first cracks (general recommendation: $f_{ct,eff} = 3$ N/mm$^2$); $l_e$ = recommended introduction length as a function of the thickness of the new concrete layer $t_n$ and the roughness of the interface:

- $l_e = 3t_n$ for highest pressure water jetting or appropriate chiselling
- $l_e = 6t_n$ for sand blasted interfaces
- $l_e = 9t_n$ for smooth interfaces

A moment is induced by the eccentricity of the resulting force $F_{cr}$ (eccentricity measured from the interface). This moment produces peeling forces acting perpendicular to the joint which can be derived from equilibrium conditions and estimated according Equation 3:

$$N_{ed} = \frac{t_n \cdot b_j \cdot k \cdot f_{ct,eff}}{6} \left[ kN \right]$$

Therefore sufficient edge reinforcement for the anchoring of these tensile loads has to be considered, which may be used for the transfer of the calculated shear stresses as well.

4.4 Anchorage of connectors in the existing and new concrete

The connectors must be adequately embedded in the existing and the new concrete overlay. The actual anchored tensile force, due to the roughness for high pressure water jetted, chiselled and sand blasted interfaces, is taken as:

$$N_{ed} = \kappa \cdot A_s \cdot \frac{f_{yk}}{\gamma_s}$$

The factor $\kappa$ depends on the geometry of the connector cross section (solid circle section or ring) as explained earlier. The appropriate embedment of the anchors can be verified according to state-of-the-art design principles (Hilti Fastening Technology Manual 2005, Eligehausen, Mallée & Silva 2005).

5 CONCLUSIONS

A new hollow injection-type connector made of malleable cast steel, the so called HCC-B element, has been designed by the Hilti Corporation to attach new structural concrete layers to existing concrete structures. Extensive laboratory tests have been performed under static and dynamic loading. The shear tests confirmed the existence of the three resisting components being cohesion, friction and dowel action along water-jetted interfaces and verified formerly obtained results (Randl 2004) conducted with post-installed rebars. The first projects in Switzerland, Germany, The Netherlands and Austria have been completed and proven the efficiency of this method in strengthening and repair of concrete structures.

REFERENCES

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