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Repair of Structures through External Bonding of Thin Carbon Fiber Sheets

Réparation de structures au moyen de lamelles en résine époxyde renforcée de fibres de carbone

Sanierung von Tragwerken durch Aufkleben von kohlenstoffaserverstärkten Epoxidharzlamellen

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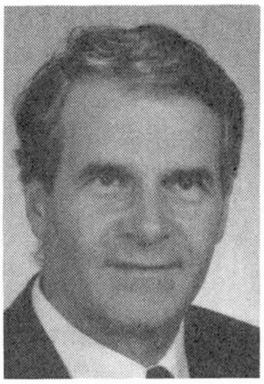

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SUMMARY

This paper seeks to demonstrate how advanced polymer matrix composite materials developed for high-performance aircraft can offer advantages for rehabilitation and retrofitting of existing civil engineering structures through external bonding of thin carbon fiber/epoxy (CFRP) sheets. Easy handling on site due to the light weight of the CFRP sheets helps to reduce labor costs. For this reason commercial use has increased in Switzerland.

RÉSUMÉ

Ce travail montre comment les matériaux composites à base de fibres à hautes performances développés pour l'industrie aéronautique et aérospatiale peuvent offrir des avantages majeurs pour l'assainissement des ouvrages d'art sous forme de minces lamelles collées en résine époxyde renforcée de fibres de carbone. Le maniement aisé de ces lamelles légères permet une économie de travail importante sur le chantier. C'est la raison pour laquelle leur utilisation commerciale a rapidement augmenté en Suisse.

ZUSAMMENFASSUNG

In dieser Arbeit wird dargestellt, wie Hochleistungsfaserverbundwerkstoffe, welche für die Luft- und Raumfahrt entwickelt wurden, neuerdings durch Aufkleben von dünnen kohlenstoffaserverstärkten Epoxidharzlamellen (CFK) zur Sanierung von Tragwerken eingesetzt werden. Die einfache Handhabung der leichten Lamellen erlaubt es, auf der Baustelle Arbeitsstunden zu sparen. Aus diesem Grund hat die kommerzielle Anwendung dieses neuen Verfahrens in der Schweiz stark zugenommen.

1. INTRODUCTION

Deterioration of reinforced and prestressed concrete bridges due to corrosion initiated by the application of deiceing salts and continual upgrading of service loads and volume of traffic on bridges has resulted in thousands of bridges the need for retrofitting. Even a much greater number of other structures require strengthening for a greater diversity of reasons. These considerations illustrate the great importance of effective renovation methods for existing structures. Thus, the method of post-strengthening structures by the bonding of steel plates or fiber-reinforced composite laminates gains in significance.

2. WHEN DO STRUCTURES HAVE TO BE POST-STRENGTHENED?

When do structures have to be post-strengthened? These measures are required when structures must take on new tasks involving increased loads. Furthermore, during the process of modernization, individual supports and walls may be removed, thus leading to a redistribution of forces and the need for local reinforcement. In addition, structural strengthening may become necessary when in the course of time damages occur due to normal usage or environmental factors.

3. CRITERIA FOR MATERIAL EVALUATION

Today in Western Europe and other parts of the world the technique of bonded steel plate strengthening is widespread and state of the art. Nevertheless, outdoor creep tests over extended time periods at the EMPA show that long-term problems concerning corrosion behavior must be expected in outdoor applications. EMPA-researcher observed "smaller traces of rust" on unprimed as well as primed steel-plate bond surfaces even after 3 years of exposure to weather. They grew larger during the course of the test. After 15 years the areas now range up to 10 mm in diameter. These tests are being continued at the EMPA and indicate a weakness in the strengthening with steel plates. However, steel plates also have other disadvantages.

During renovation work, particularly on bridges, only a limited amount of mechanized lifting machines are available on site. In the interior of box girders for example the strengthening plates have to be carried to the point of installation by hand. Due to handling limitations on site the steel plates are rarely longer than 6 to 8 m. Thus, if the strengthening work involves greater lengths, the plates must be abutted. Abutments cannot be welded together since the welding temperatures would destroy the bond. For this reason abutments of steel plates have to be formed from single-shear lap joints. On the other hand, high-strength fiber composite laminates are relatively thin and can be delivered to the construction site in rolls, in lengths of up to 300 m or more. Compared to steel plates their application is greatly simplified.

The first task was to find the best suitable fiber composite material for this application. The results shown in [1, 2] clearly show that carbon-fiber reinforced plastic laminates most closely fulfill the requirements for the post-strengthening of structures. Therefore all further discussion will be restricted to carbon-fibre reinforced plastics (CFRP).

4. MANUFACTURE OF CARBON-FIBER REINFORCED PLASTIC LAMINATES

The laminates are manufactured using a pultrusion process. The pultrusion principle is comparable with a continuous press. Normally 12k rovings (12,000 parallel filaments) are pulled through the impregnated bath, formed into laminates under heat and thereafter hardened. These laminates are unidirectional, i.e. the fibers run only in the longitudinal direction. Correspondingly the laminate strength in this direction is proportional to the fiber strength and therefore very high. In Switzerland (Stesalit AG, 4234 Zullwil, Switzerland) laminates are now made of Toray T700 fibers with a fiber strength of 4,900 MPa. With a fiber volume fraction of about 65% the resulting laminate strength amounts to about 3,000 MPa in the longitudinal direction.

5. COMPOSITE OF FIBER REINFORCED PLASTIC (CFRP) AND CONCRETE

In order to achieve an optimum composite, the preparation of the bonding surfaces of the two composite partners is very important. The CFRP laminates must be well ground on the bonding side. The outermost layer, normally matrix-rich, has to be removed to expose the fibers. Just before bonding, the bonding surface has to be carefully cleaned. This must be repeated until the washcloth no longer blackens. The concrete surface is treated by sand blasting, high pressure water jets, stoking or grinding; shortly before the bonding it is cleaned with a vacuum cleaner. The concrete must be at least 6 weeks old with a tensile strength of 1.5 MPa or higher.

Classical, highly filled epoxy resin adhesive is employed for the bonding. The adhesive is applied Λ-shaped to the CFRP laminate so that the extra adhesive is squeezed out when the laminate is pressed to the concrete structure. For a laminate width, for example, of 200 mm, the "peak height" in the middle of the laminate amounts to about 10 mm. The laminates must be pressed to the concrete until hardening using vacuum bags or other techniques. The methods developed by the EMPA are described in detail by Deuring [3].

6. CONSIDERATIONS FOR NOT PRETENSIONED, BONDED CFRP LAMINATES

In the middle of the 1980's, based on tests with middle sized beams, it was shown (Meier [4]) that post-strengthening with CFRP laminates is possible. As a result of comprehensive investigations at the EMPA Kaiser [5] came to the following conclusions:
Post-strengthening of structural components with CFRP laminates may be calculated in flexure analogously to conventional reinforced concrete. Special attention must be paid to the formation of shear cracks in the concrete. Such shear cracks lead to an offset on the strengthened surface. This generally causes a peeling-off the strengthening laminate. Thus, shear crack formation is a design criterion. Flexure cracks are spanned by the laminate and do not influence the carrying capacity. The carrying capacity can be predicted accurately in advance.

The calculation model for the anchoring of the laminates agrees with experiments over a wide range. For short anchoring lengths the model underestimates the carrying capacity of thick laminates and overestimates it for thin laminates .

Bonded CFRP laminates have a very positive influence on crack development of a reinforced concrete beam. The cracks are more finely distributed and the sum of the crack widths is greatly reduced. Even after exceeding the yielding point of the inner reinforcement the crack growth remains under control up to failure thanks to the elastic CFRP laminate.

CFRP laminates exhibit excellent fatigue behavior. Through the bonding of the CFRP laminate the inner reinforcement is relieved. Tests with very high vibration amplitudes yielded excellent results [5] over more than 10 million load cycles.

7. DESIGN FOR PRETENSIONED, BONDED CFRP LAMINATES

In EMPA Report Nr. 224 [3] Deuring shows the potentials of pretensioned laminates. Following the pre treatment of the laminate and concrete surfaces described above the CFRP laminate is tensioned to 1,000 MPa using a special tensioning device. The adhesive is applied before pressing the tensioned laminate to the structure. After hardening of the epoxy resin the force-transfer zones at the laminate ends are provided with pressure plates in order to transfer the large forces of the laminate into the concrete. As a result of a pressing force perpendicular to the laminate surface the shear strength of the concrete is increased; if horizontal micro cracks occur, the laminate remains successfully anchored to the structure owing to the effective interlocking of the laminate. Finally, the external tension is lowered and the structure is not only strengthened through a CFRP laminate, it is as well prestressed . In this way, even existing cracks can be closed.

Deuring [3] comes to the following conclusions: The calculation procedure closely predicts the load behavior of a structure post-strengthened with a pretensioned CFRP laminate. Since the CFRP laminate has no plastic deformation reserve the highest flexural resistance of a strengthened section is reached when laminate failure occurs simultaneously with the yielding of the steel and before the concrete fails. The type of failure is strongly influenced by the laminate cross-section and the tensioning force. Tension and deformation calculations may be carried out with conventional methods. Test results on realistic beams confirm the validity of the classical assumptions. Pretensioning reduces the danger of peeling off, mentioned above for non-pretensioned laminates. The total sum of the crack widths is influenced even more favorably than with non-pretensioned laminates. The excellent fatigue behavior exceeds all expectations.

8. SOME APPLICATION EXAMPLES IN BRIDGE AND BUILDING CONSTRUCTION

The Ibach Bridge [6], built in 1969 is located in Emmenbrücke, a suburb of Lucerne/Switzerland. It crosses over National Highway N2 (Basel-Gotthard-Chiasso) and the Emme and Reuss rivers. The bridge is designed as a continuous beam structure with 7 spans and a total length of 228 m. In the span, which crosses the six lane N2, a prestressed cable in a web was accidentally cut. The repair work was undertaken in the Summer of 1991. Three CFRP laminates with a total mass of 6.5 kg were bonded. In order to have obtained the same results with steel 175 kg would have been necessary. Results of loading tests show that experimentally measured elongations agree with the calculated values. This strengthening was carried out by the firm StahlTon AG, 8034 Zurich.

The historical Wooden Bridge in Sins/Switzerland [6], constructed in 1807, crosses the Reuss river and consists of two spans, each of 30.8 m length. Problems arose with the crossbeams. Under the permissible load of 200 kN per vehicle the oak beams exhibited excessive deflection. To limit this deflection the beams subjected to the highest loads were successfully stiffened in the spring of 1992 with CFRP laminates having a longitudinal modulus of elasticity of 300 GPa.

An elevator was to be subsequently installed in the City Hall of Gossau St. Gall/Switzerland [6] in 1991. Before cutting the elevator cross-section from the reinforced concrete roof the "replacement reinforcement" in the form of CFRP laminates was bonded to the "future" edges. In this example the CFRP laminates were employed for aesthetic reasons. The architect wanted to make the post-strengthening invisible; this succeeded very well as the laminates were only 1 mm thick. In this case, corrosion, mass and fatigue behavior were no criteria.

In Spring 1993 the Migros Supermarket in Uzwil/ Switzerland was expanded. In order to connect the new sales area with the old one the existing outer wall, a supporting brick construction, had to be removed over a length of 13 m. The building contractor did not want any additional supports in the new passage. The carrying capacity of the existing parking deck had to be maintained. The individual strengthening laminates were 15.5 m long. With steel plates the installation weight would have amounted to 120 kg compared to 3.5 kg with CFRP laminates.

Major projects followed in 1994: The Main Railway Station in Zurich where the load carrying capacity of a large, heavy loaded concrete slab had to be increased by a factor of 1.4 and the huge chimney of the Nuclear Power Plant Leibstadt, where the safety factor was of outstanding importance. All these cases described above were executed again by the firm StahlTon AG.

The ceiling in the tankroom of the Paper Mill in Utzensdorf (Switzerland) had to be reinforced due to the installation of a new machine unit. The reinforcement was performed in January 1995 with forty meters of CFRP sheets. The advantages of the CFRP strengthening method were decisive for the contractor due to the low working height of only 800 mm above the tanks and the small entrance recess into the tankroom. The ultimate tensile load capacity of this type of CFRP sheet is 210 kN per sheet and the dead weight is only 140 grams per meter. This CFRP sheets have been developed by Hilti in co-operation with EMPA and they were offered by Kilcher HBC, the Hilti representative for rehabilitation systems in Switzerland.

Until January 1995 there were approximately 80 applications of the method of external bonding of thin carbon fiber/epoxy (CFRP) sheets in Switzerland.

9. OUTLOOK

Based on the research and development work at the EMPA the application of CFRP laminates is already almost routine for the firms StahlTon AG in Zurich, Sika AG in Zurich and Kilcher HBC, the Hilti representative for rehabilitation systems in Switzerland, in the strengthening of existing structures. Originally it had been assumed that this technique would only be cost-efficient if there were very high requirements relative to corrosion, fatigue performance and light weight. However after further price decreases of carbon fibers this method has become also cost efficient for applications in which not all of these requirements are present.

In our opinion fiber composites have excellent chances in specific civil engineering applications as described here or for seismic strengthening [7, 8] or for stay cables [9]. However, even in the future when further decreases in price of carbon fibers can be expected they will not replace classical materials such as steel, concrete and wood but rather supplement them as called for.

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