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THE PREMATURE FAILURE OF CFRP LAMINATE-STRENGTHENED CONCRETE STRUCTURES: EXPERIMENTAL AND THEORETICAL FINDINGS, AND CONCLUSIONS FOR DIMENSIONING

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Abstract. *Experimental investigations on CFRP laminate-strengthened concrete beams show that the most common failure mode is laminate peel-off. This process often happens within a fraction of a second, and is therefore very difficult to study in order to find suitable dimensioning rules.*

This report presents an innovative measurement method which was used to monitor the delamination process. Two experiments provided different results: in test beam PS4, peeling-off started in the shear crack region while in beam ET delamination started at the laminate end. An analytical analysis of the beams at failure aims to explain those observations. The findings demonstrate that for both cases delamination can be prevented by consideration of some special dimensioning aspects: the shear stresses in the laminate–concrete interface must be restricted and the anchorage resistance must be verified. Concerning bridge engineering some general strengthening rules can be derived which give answers to questions like "is the use of CFRP laminates reasonable?" and "how shall the laminates be arranged?".

1 INTRODUCTION

The use of carbon-fibre-reinforced plastic (CFRP) laminates for flexural strengthening of concrete structures has been investigated since the 1980's. In the early 1990's buildings were first strengthened (Meier [6]) and engineers from different institutes in the world started to study the use of CFRP products for the repair of different types of structures. Since then, research and application activities have grown constantly, and today many publications and strengthened structures can be found (Meier [7]).

In his early investigations Kaiser [4] used conventional reinforced concrete beams with a span of 2 m. He applied CFRP laminates on the tension face and tested them in four-point bending. In spite of a considerable strengthening effect (in comparison to the unstrengthened reference beam) he observed that the laminates generally peeled off before their material strength was achieved. Since then, many engineers have performed similar tests and also observed this premature failure mode (e.g. Deuring [1], Wendel [11]).

This paper aims at giving an experimental and theoretical analysis of the peeling-off problem, and drawing conclusions applicable to strengthening tasks in structural engineering.

2 THE PREMATURE FAILURE OF CFRP LAMINATE-STRENGTHENED CONCRETE BEAMS

2.1 Description of the peeling-off process

Under increasing load a strengthened beam passes from state I (uncracked) to state II (cracked) and generally to state III (cracked, yielding of the internal steel reinforcement) before failure occurs. Depending on the beam's geometry and material properties, different failure modes are possible. A high reinforcement ratio will cause failure of the concrete compression zone and very thin laminates will rupture due to exceeding of the material strength. These two failure modes will not be discussed further. When commercial products are used in typical strengthening arrangements, the most probable failure mode is laminate peel-off.

Kaiser [4] observed that laminates peel off when shear cracks start to grow. In his opinion, the process is initiated by a vertical displacement in the lower beam face due to opening of inclined shear cracks. In later investigations some researchers suggested a second theory to explain the laminate peel-off. They claim that this process starts due to stress concentrations at the laminate end. Today, most engineers accept both the shear crack region and the laminate end theory (e.g. El-Mihilmy and Tedesco [2], Wendel [11]). Nevertheless, in experimental investigations it often turns out to be impossible to find the origin of the delamination. The whole process happens within a fraction of a second and therefore can not be observed with conventional measuring techniques.

2.2 The Silver Paint Method

In order to investigate the debonding process, an innovative but simple measurement method has been established and applied: the Silver Paint Method.

The principle of the method is simple: Conductive paint is used to draw eight continuous stripes (S1 … S8) which cross the laminate. An oscilloscope is used to monitor the conductivity of each stripe with an frequency of 100 kHz. When a crack plane has separated the laminate from the beam, the electric current is interrupted. For every silver paint stripe the moment of interruption can be determined and used to describe the delamination process.

2.3 Experiments

The beams PS4 and ET were used to examine the delamination process. The cross-sections and the material properties are given in Table 1. Figure 4a) shows the longitudinal dimensions and the load arrangements.

Beam PS4

In a series of four-point bending tests beam no. 4 was equiped with the silver paint measuring system. Some previous beams had failed by sudden laminate peel-off, therefore the need for this extra measurement arose.

Beam ET

Beam ET was a larger beam which was subjected to 10 million load cycles before an ultimate load test was carried out. In this way the fatigue performance of structures with this type of strengthening could be studied

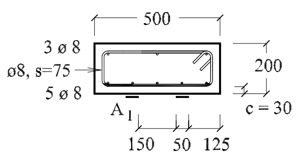
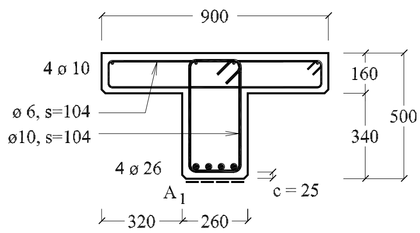
<table>
<tr><td>Cross-section</td><td>PS4:

</td><td>ET:

</td></tr>
<tr><td>Beam
-span
- number of laminates</td><td>
2.1 m
2</td><td>
6.0 m
4</td></tr>
<tr><td>Material properties</td><td colspan="2">concrete: f_c = 26 MPa, f_{ct} = 2.2 MPa, E_c = 35 GPa.
steel: f_y = 500 MPa, E_s =200 GPa
CFRP laminate: t_l = 1.2 mm, b_l =50 mm, E_l = 130 GPa.</td></tr>
</table>

Table 1: Cross-sections and material properties

2.4 Results

The load-midspan displacement diagrams are given in Figure 1. Figure 2 displays photographs of the beams at failure. The silver paint stripes and the corresponding moments of current interruption (in milliseconds) are indicated. These times give the location of the propagating tip of the laminate–concrete separating crack.

In case of PS4 the measurement shows that the crack had interrupted the stripes in the sequence S8 – S7 – S6 – S3 – S4 (for unknown reasons, S5 failed before delamination was initiated). This observation shows that peeling-off started at the laminate end, in the vicinity of the right beam support.

The laminates on ET peeled off differently: the silver paint stripes were interrupted in the sequence S3 – S2 – S1 – S4 – S5 – S6. The delamination origated in the vicinity of stripe S3, propagated to the left support and finally towards the right support.

In PS4 delamination started at the laminate end while in beam ET the peeling-off started in the shear crack zone. Hence, both of the previously stated laminate peel-off theories seem to be valid and must be considered for dimensioning tasks.

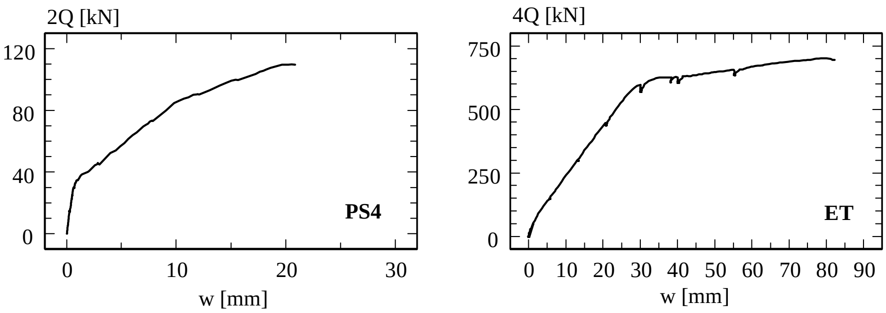


Figure 1: Load-displacement diagrams

PS4:

ET:

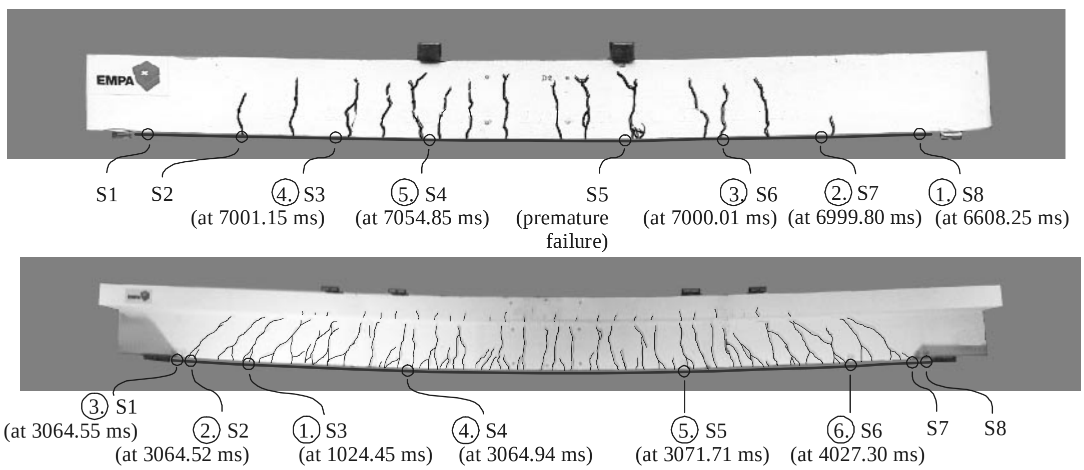


Figure 2: Sequence of failure of silver paint stripes

3 ANALYTICAL ANALYSIS OF CFRP LAMINATE STRENGTHENED CONCRETE BEAMS

3.1 Basics

Consider a conventionally reinforced concrete beam strengthened with CFRP laminates that serve as an additional tension chord to increase flexural resistance. The structure is mainly subjected to flexural load, the influences of shear and normal force will not be considered.

The design fundamentals are the elementary basics for the analysis of conventionally reinforced concrete structures (Leonhard [5]):

- The *materials* are characterized by idealized stress-strain relations (SIA Norm [8]), (Figure 3a)).
- Plane sections remain plane *(compatibility requirement),* (Figure 3b)).
- *Equilibrium of forces* is connecting the applied load to the internal forces (Figure 3b)).

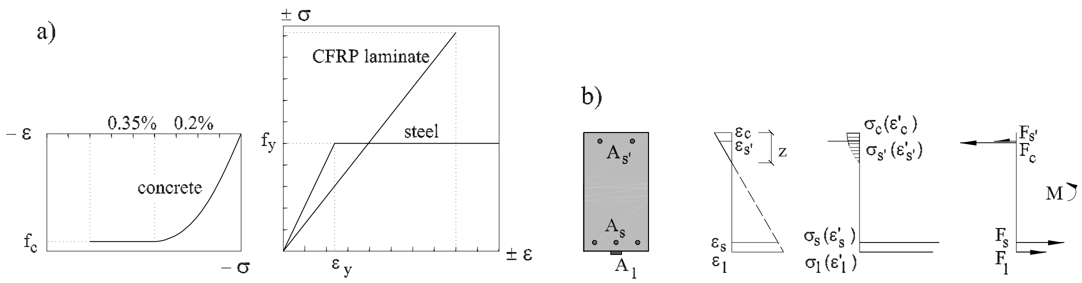


Figure 3: Design fundamentals: a) stress-strain relations of materials;
b) compatibility requirement and equilibrium of forces in the cross-section

3.2 Cross-sectional analysis

The cross-sectional analysis aims at finding the corresponding strains and stresses when flexural loading is applied.

The compatibility requirement in Figure 3b) is valid for average deformations (strains, ε). To formulate the equilibrium of forces, the strains and stresses in the cracks (ε'') must be determined. Therefore a simple relation can be used:

$$\varepsilon_l'' = \frac{\varepsilon_l}{\kappa_l} \qquad \varepsilon_s'' = \frac{\varepsilon_s}{\kappa_s} \tag{1}$$

The bond coefficient, κ, characterizes the quality of the bond between the reinforcement (steel bar or CFRP laminate) and the concrete. It can vary from 0.0 (perfectly rigid bond) to 1.0 (poor bond). The "real" value is virtually impossible to determine. However, since this is not of significant importance for the global considerations, the following assumption will be used: $\kappa_l = \kappa_s = 0.8$.

The stresses and forces in Figure 3b) can be determined from the strains in the cracks and equilibrium can be formulated. The mathematical treatment provides a set of equations and the use of a computer with mathematical or spreadsheet software is recommended for numerical evaluation.

3.3 Analysis of PS4 and ET at failure

The measured failure load combined with the dead load of the beams provide the bending moment lines given in Figure 4b). In accordance with the explanations given in the previous sections, a comprehensive cross-sectional analysis was carried out (corresponding to Ulaga [10]). Figure 4c)-e) show results from this analysis.

3.4 Critical zones

Anchorage zone

Holzenkaempfer [3] established a set of formulas that can be used to determine the anchorage capacity of laminates bonded to concrete. For the treatment of the present problem the following expression is suitable:

$$F_{bR} = b_l \cdot \sqrt{2 \cdot G_b \cdot E_l \cdot t_l} \cdot \tanh \sqrt{\frac{\tau_{l1}^2 \cdot l_b^2}{2 \cdot G_b \cdot E_l \cdot t_l}} \qquad (2)$$

Evaluation of this formula with appropriate parameters provides the anchorage resistance for PS4 and ET.

PS4: $F_{bR} = 18{,}3$ kN [1)]

[1)] ($G_b = 0.5$ N/mm; $\tau_{l1} = 5$ MPa; $l_b = 132$ mm; b_l, t_l, E_l according to Table 1)

ET: $F_{bR} = 6{,}6$ kN [2)]

[2)] ($G_b = 0.5$ N/mm; $\tau_{l1} = 5$ MPa; $l_b = 27.5$ mm; b_l, t_l, E_l according to Table 1)

The anchorage zone is located in the uncracked area of the beam, behind the last crack. In order to find the appropriate laminate tension force the corresponding stress value from Figure 4d) can be divided by κ_l (Equation 1). At the edge of the uncracked region the bond is good, therefore a value of $\kappa_l = 0.4$ is reasonable. With these assumptions, the following laminate tension forces are estimated:

PS4: $F_b = 19{,}8$ kN [1)]

[1)] = (132 MPa·50 mm·1.2 mm)/0.4

ET: $F_b = 5{,}2$ kN [2)]

[2)] = (35 MPa·50 mm·1.2 mm)/0.4

In PS4 the laminate tension force exceeds the anchorage resistance while in ET it remains slightly lower. This corresponds with the experimental result confirming the origin of debonding at the laminate end in PS4.

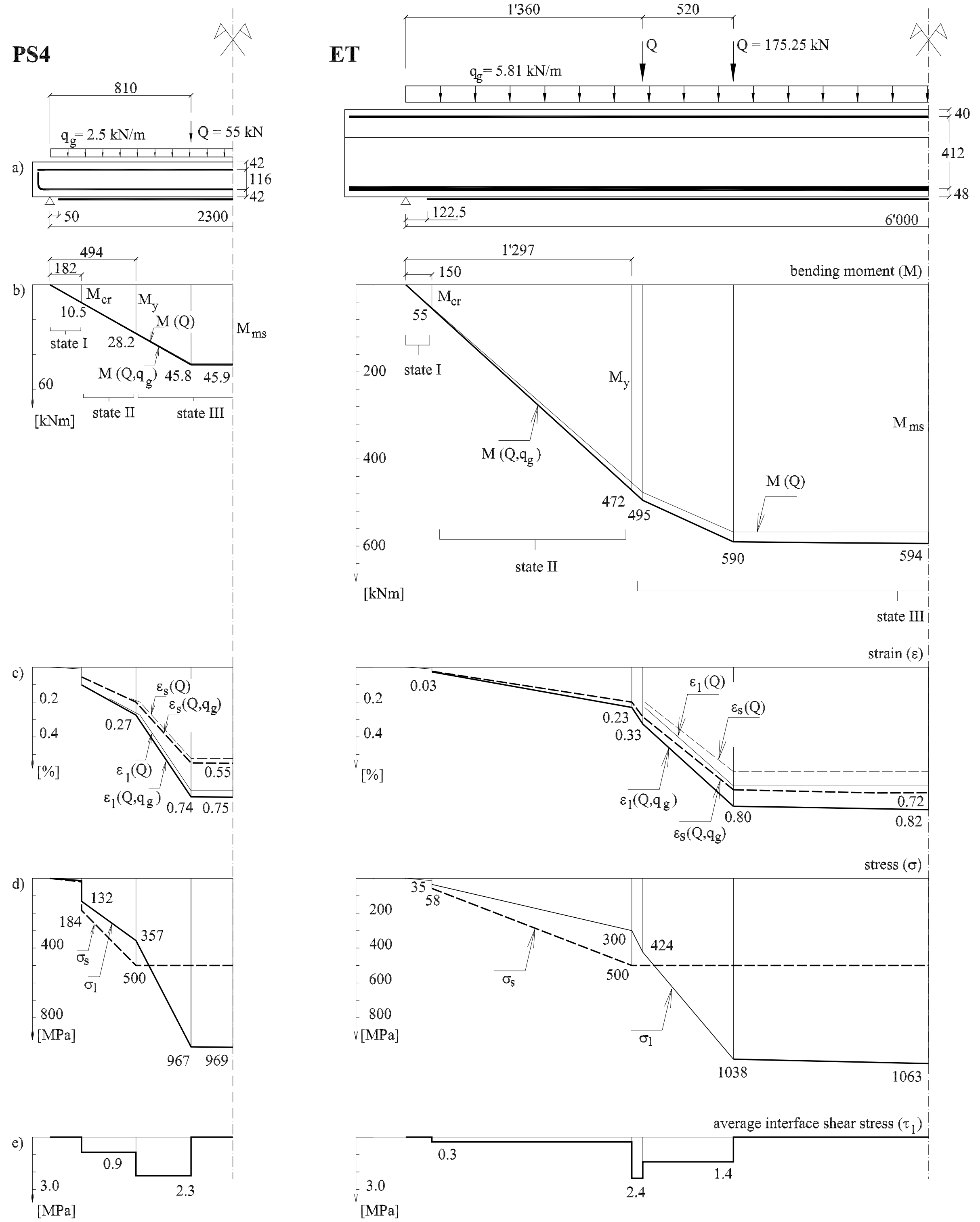


Figure 4: Cross-sectional analysis: a) Structure and load arrangement; b)–e) Diagrams derived from the analysis

Shear crack region

The shear crack region is dominated by considerable shear stresses at the laminate–concrete interface. These values can easily be determined from the change of the laminate tension stress:

$$\tau_l = \frac{\Delta\sigma_l}{\Delta x} \cdot t_l \tag{3}$$

Hence, diagram e) can be derived from diagram d) in Figure 4.

In PS4 and ET, the maximum average shear stresses are 2.3 and 2.4 MPa, respectively (in the vicinity of cracks even higher shear stresses occur). These values exceed the concrete tension strength given in Table 1. Even though the average shear stress and the tensile strength should not be compared directly, the relation between these two values indicates a considerable failure potential for both beams.

4. CONCLUSIONS

General conclusions

- The laminate peeling-off process can be initiated in both the shear crack region and the anchorage zone.
- In order to prevent delamination, the anchorage resistance must be verified and the shear stress at the laminate–concrete interface must be restricted.

Conclusions concerning strengthening of concrete bridges

- Laminates must be anchored in uncracked areas of a structure. Therefore, the laminate end must be located as close to the support as possible.
- Due to shear stresses at the laminate–concrete interface, narrow but thick laminates are less effective than wide and thin ones.
- The use of CFRP laminates can be recommended for the strengthening of parts of structures which are predominantly subjected to distributed loads. Concentrated loads usually cause high shear stresses which lead to a considerable failure potential.

NOTATION

A	cross-sectional area	*g*	gravity	ε	strain	*cr*	crack
G	specific energy	*l*	length; span	κ	bond coefficient	*l*	laminate
E	modulus of elasticity	*q*	distributed load	σ	normal stress	*ms*	midspan
F	force	*s*	stirrup distance	τ	shear stress	*s*	steel; distance
M	bending moment	*t*	thickness			*s'*	steel at compression
Q	single load	*w*	width; deflection	**Subscripts**		*t*	tension
S	silver paint stripe	*x*	coordinate	*b*	bond	*y*	yield
b	width; bond	*z*	compression zone depth	*1*	index "at maximum"		
c	concrete cover			*R*	resistance	**Superscripts**	
f	strength	Δ	difference	c	concrete	"	in the cracks

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