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A New Method and Device for Application of Bonded Pre-stressed FRP Laminates

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Abstract— **Using bonded fiber reinforced polymer (FRP) laminates for strengthening and repair of structural members has been proven to be an effective and economic method. High strength and stiffness, light weight and good fatigue and durability properties of FRP composites together with advantages offered by adhesive bonding have made it a suitable alternative for traditional strengthening and repair techniques. It has also been recognized that pre-stressing the FRP laminates prior to bonding would bring additional advantages such as reduced crack widths, postponing the yielding in tensile reinforcement, increasing the load bearing capacity and saving reinforcement material. Using pre-stressed laminates, however, is associated with very high interfacial stresses in the bond line at the laminate ends, which necessitates the use of mechanical anchors. This paper presents a new method and a device for applying pre-stressed FRP laminates to flexural structural members without the need for mechanical anchorage of the laminates. The principle of the method is based on controlling the interfacial stresses in the bond line using a non-uniform pre-stressing force profile. The principle of the method along with lab verifications and field applications are presented and discussed.**

***Keywords—FRP*, pre-stressing, strengthening, anchorage.**

I. Introduction

The large stock of existing bridges in Europe and elsewhere in the world is in urgent need for rehabilitation including strengthening and repair. Majority of existing bridges are relatively old and have been subjected to various degradation mechanisms through their service life. In addition, the traffic intensity and allowable axel loads have increased substantially over the time to accommodate the increasing demands exerted on modern transportation networks. This has in recent year’s motivated intensive focus on research and development of effective methods for strengthening and upgrading of existing bridges around the world.

Rehabilitation measures, especially strengthening and repair works, are among the most disturbing activities at bridge sites and as the subject of “sustainable construction methods” takes more attention in the construction sector, there is an interest among bridge authorities towards using more cost efficient and less disruptive maintenance methods.

In this context, using externally bonded fiber reinforced composites, FRP, mostly carbon fiber reinforced polymer, CFRP, for strengthening and repair of bridge structures has attracted a great deal of attention. FRP bonding is rather straight forward. Firstly, the surface of the structural members is prepared to remove any contaminations and to provide a good bonding surface. The laminates are cut in suitable lengths and bonded to the surface by means of a structural adhesive, mostly epoxy.

Large number of CFRP bonding applications in the world shows the potential of this technique for strengthening and repair of structures. The large difference in modulus of elasticity of concrete and CFRP composites makes it ideal for strengthening concrete structures, since at already small deformations the CFRP material is activated as a load bearing agent and contributes in stiffness and ultimate strength of the structural member.

In order to obtain a large contribution of CFRP strengthening in load bearing capacity, a large transfer of force to CFRP laminate is necessary. Study of the force transfer mechanism in adhesive joints shows that a large portion of the force is normally transferred at a rather short distance at the ends of the laminate referred to as anchorage length. The larger the difference between the modulus of elasticity of concrete and CFRP material, the higher the force carried by the FRP laminate which leads to higher shear stresses along the anchorage length in the adhesive layer and the concrete material. Due to the limited strength of concrete in shear and tension, the failure of CFRP bonded concrete members is usually governed by debonding of the CFRP laminate at concrete cover layer. Debonding reduces the utilization of the composite laminate and is usually characterized by sudden separation of the strengthening laminate from the structural member. This is an unfavorable failure mode since debonding usually takes place way before the CFRP laminate reaches its ultimate strength. This phenomenon dramatically reduces the efficiency of the strengthening. A substantial amount of research has been devoted to finding possible solutions to increase the efficiency of FRP bonded strengthening systems. One suggested solution is to postpone the debonding of the strengthening laminate from the concrete substrate using anchoring systems at the ends of the composite laminates [1].

Another solution to exploit the full capacity of the FRP laminate is to use pre-stressing in the composite material before bonding to the structural member. This solution has been the subject of several studies since 1990th, see for example [2-6]. The idea is to induce a pre-stressing force which enables the composite laminate to build up stress/strain up to failure. Application of pre-stressing force in the laminate results in an active strengthening system (unlike the non-prestressed systems) which enhances the overall structural

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behavior of the strengthened member in a number of ways [7]. Pre-stressing would result in enhanced SLS by reducing the deflections, reduced crack width, delay in onset of cracking, unloading the tensile reinforcement and thus better fatigue resistance, enhanced ultimate load carrying capacity, enhanced shear capacity [8] and reduction in the amount of needed strengthening material [fib Bulletin 14(10)].

A major problem with using pre-stressed CFRP laminates is the tendency of the strengthening laminate to debond at already very low pre-stressing levels. Triantafillou et al. [9] showed that the premature failure of a concrete beam strengthened with a CFRP strip, without any anchorage system, took place immediately after the release of the pre-stressing force. Horizontal shear cracks propagated from both ends of the CFRP strip through the concrete layer. The authors suggested that the failure may be prevented by using a mechanical anchorage system. It was shown that the maximum pre-stressing force that could be managed without mechanical anchors was about 15% to 20% of the strip ultimate strength depending on the properties of the CFRP strip. El-Hacha et al. [10] suggested that pre-stressing levels of up to 25% might be necessary to achieve a noticeable improvement in structural stiffness and load carrying capacity. Meier [11] suggested that a pre-stress level of 50% of the CFRP strip strength may be necessary to increase the ultimate strength. Therefore, in general, a mechanical anchorage system is necessary to prevent premature debonding [9].

There are a number of commercially available anchorage systems to be used in conjunction with pre-stressed composite laminates, such as the LEOBA and StressHead systems developed by Sika [www.sika.com] and S&P clever reinforcement. In all these systems, a mechanical anchorage is used to transfer the high pre-stressing force from the laminate to the strengthened member, and thus prevent debonding. Mechanical anchorage systems, typically, include steel or aluminum plates [12-14] or, non-metallic anchors [15]. Application of mechanical anchors involves a number of problems namely: (1) need for extra modification of the structural member (e.g. cutting concrete for fitting anchor plates, drilling holes, etc.), (2) concerns about long-term performance, (3) difficulty of inspection and need for extra maintenance of anchors, (4) extra cost needed for mechanical parts to be installed and the time needed for preparatory work for installation of anchor plates. It is worth of mentioning that the pre-stressing level might be limited by the strength of the mechanical anchors. The most important concern regarding the use of mechanical anchors is, however, the long-term performance.

This paper introduces a new method and a device to apply pre-stressed FRP laminates to structural members without the need for mechanical anchorage. Using this technique, therefore, eliminates many of the shortcomings associated with application of mechanically anchored pre-stressed FRP laminates.

II. Principle of the new method

Considering the closed from solutions developed for calculation of shear stresses in a beam strengthened with a pre-stressed laminate (see for example [16]), it could be seen that the magnitude of the shear stress along the bond line in the adhesive layer has a direct relationship with the rate at which the axial force develops in the laminate. In other words, the shear stress is proportional to the first derivative of the axial force in the laminate.

Based on this fact, some researchers have proposed methods to reduce the gradient of the force in the laminate, i.e. pre-stressing force, to control the magnitude of the interfacial stresses in the adhesive joint. Research work in this area was first proposed by Wu [17] and Meier and Stöcklin [18]. Wu [17] used several layers of pre-stressed FRP sheets. The layers were successively cut towards the ends of the sheets and each layer was anchored to the concrete beam with a U-shaped FRP sheet. Meier and Stöcklin [18] developed a gradient anchorage system which was based on reducing the pre-stressing force in the strengthening laminate in a number of steps towards the end of the laminate. The method makes use of a stepwise releasing of the pre-stressing force along with a stepwise curing of the adhesive between the laminate and the strengthened beam. Adhesive curing at elevated temperature is therefore needed here and a special computer controlled device and an integrated heating system was developed to ensure a successful application. The problem with this system, however, is the time needed to complete each pre-stressing step and the complexity involved in different steps of the work including force release, curing of adhesive in each step, etc. which limits the number of steps that could be applied in practice.

The method presented in this paper differs from that proposed by Meier and Stöcklin [18] in a way that that it is based on stepwise introduction of the pre-stressing force in the laminate, rather than gradual release of the pre-stressing force. In this method the pre-stressing force is gradually introduced into the laminate in a discrete or continuous manner to achieve a force distribution similar to that shown in Figure 1. The special force transfer mechanism would reduce the magnitude of shear and peeling stress down to a level which could be tolerated by the joint constituents including the composite laminate, adhesive and the concrete substrate, eliminating the need for any mechanical anchorage system.

The principal is shown in Figure 1. As seen, the length of strengthening is divided to several steps. In each step the magnitude of the axial stress is constant. The rise in the shear stress is prevented by keeping the difference between the magnitudes of the axial force in each subsequent step at a minimum. Therefore, these intervals break the high shear stress curve and distribute it along a specific length of the laminate. Numerical and experimental studies proved that it is possible to reduce the shear and peeling stresses in the bond line to levels below 1 and 0.2 MPa, respectively, for a pre-stressing force of 100 kN by distributing the pre-stressing force over ten steps. These values are well below the shear and tensile strengths of regular concrete C35/45 which are around 10 MPa and 3 MPa respectively.

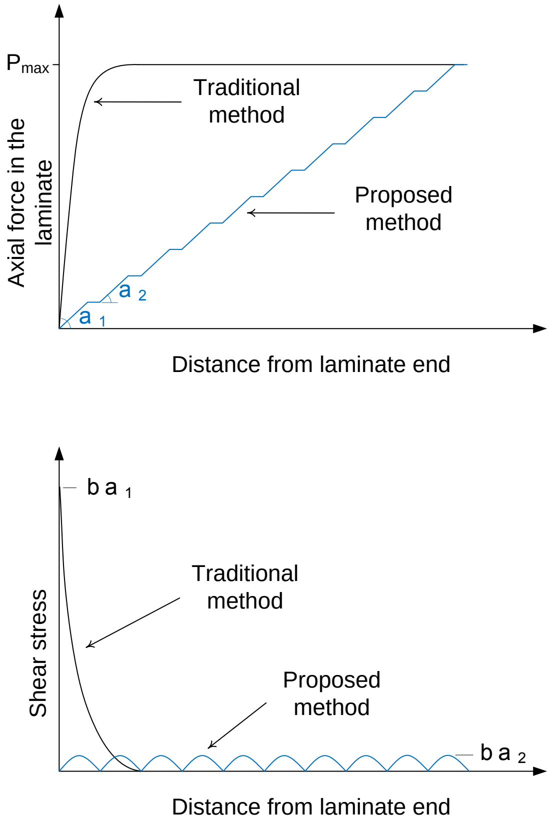

Figure 1. Geometry of specimens used in this study

III. The pre-stressing device

In order to transfer the pre-stressing force to the laminate a special pre-stressing device was designed. The device consists of ten tabs connected to each other using a series of springs. The stiffness of the springs is designed in way that they deliver 10% of the total pre-stressing force to each tab and eventually the laminate. The device is connected to the CFRP laminate via a medium, e.g. a thin glass fiber plate, which is bonded to the CFRP laminate and screwed to the device as shown in Figure 2. The principle schematic is illustrated in Figure 3.

IV. Experimental verification

The method and the pre-stressing device were verified through laboratory tests. A concrete beam with a cross section of 250x350 mm^2 was casted. In order to make a comparison between the behaviors of the beam due to pre-stressing, the beam was load up to 130 kN without reinforcement. The aim was to make the concrete beam crack in the tensile zone and investigate the effect of pre-stressing on the initial stiffness of the cracked beam. The beam was then strengthened with a pre-stressed CFRP laminate. The laminate had a cross section of 80x1.4 mm^2 with modulus of elasticity of 165 GPa and ultimate strength of 2300 MPa. It was pre-stressed with a force of 85 kN equivalent to 760 MPa, i.e. ca. 33% of the laminate ultimate strength. The pre-stressing setup is illustrated in Figure 2.

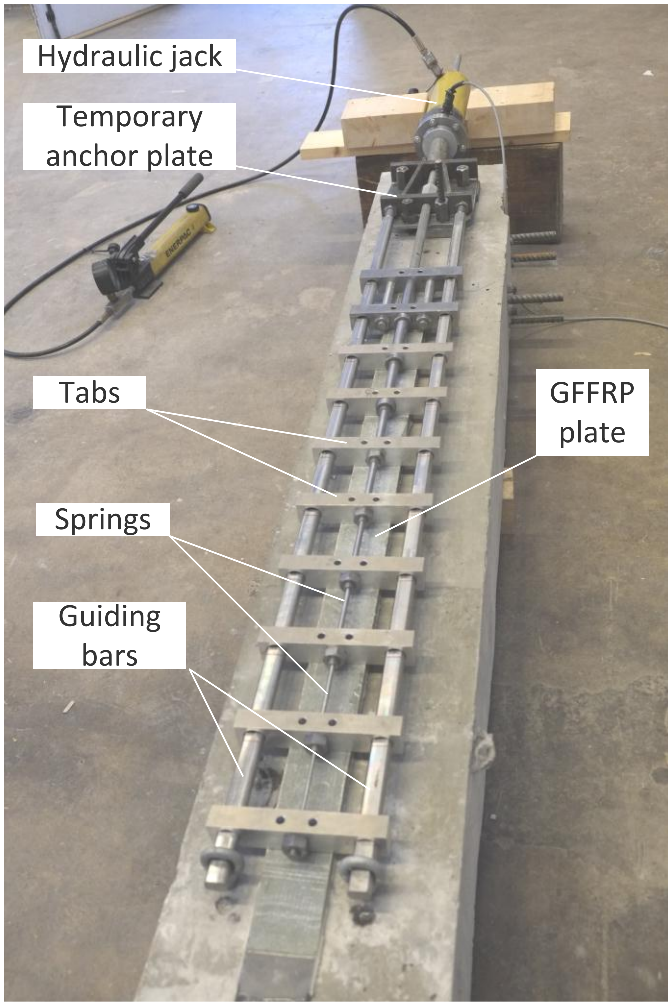

Figure 2. Pre-stressing device and setup during pre-stressing

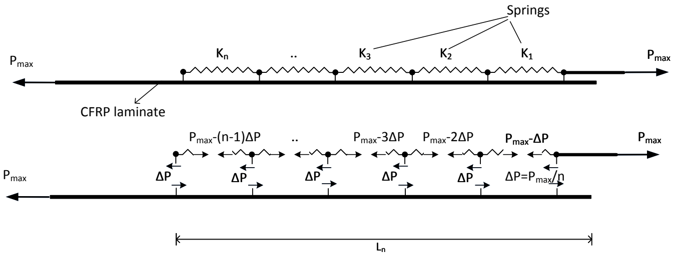

Figure 3. principle schematic of the pre-stressing device

The beam was again tested under four point bending configuration until the strengthening system failed. The test setup is illustrated in Figure 4. Figure 5 shows the load-displacement curves for the concrete beam with and without strengthening.

It could be observed that the pre-stressing increased the stiffness of the cracked beam by 40%. The failure mode of the strengthening was governed by rupture of the laminate which indicated full utilization of the composite laminate.

Figure 4. Concrete beam strengthened with pre-stressed CFRP laminate under four point bending test

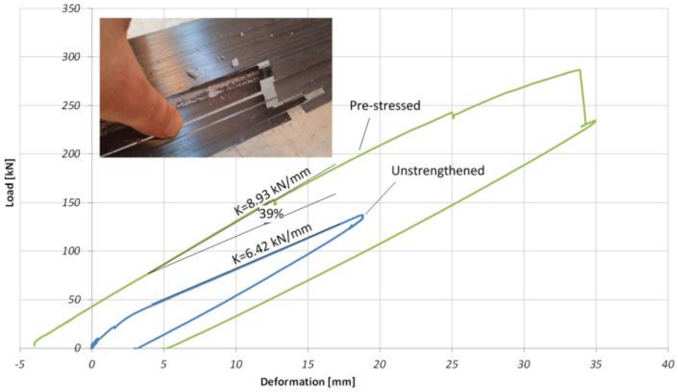

Figure 5. Load-Displacement curves of the concrete beam before strengthening and after strengthening and associated failure mode

V. Field applications

Three field applications have been carried out using this technology. The first field application of this method was carried out in collaboration with the Swedish Transport Administration. The purpose of the project was a feasibility study to evaluate the practicality of the method and possible complications during the operation. A bridge consisted of two arch girders and a concrete slab was selected for this purpose. As it was not possible to bond the laminates under the girders, they were installed on the sides of the girders as seen in Figure 6. Two laminates with cross section of 80x1.4 mm^2 were pre-stressed with a force of 100 kN and bonded to the girders. The strengthening was performed without any complications.

The second project was also performed in collaboration with the Swedish Transport Administration in which a multi span bridge was strengthened using different strengthening techniques including the proposed method in this paper. One of the girders on this bridge was strengthened using three pre-stressed laminates with a cross section of 80x1.4 mm^2 with pre-stressing force of 110 kN per laminate. The bridge was then loaded to failure. The results showed satisfactory behavior of the strengthening scheme. The results are under further investigations.

Figure 6. Strengthening of The Nossan bridge in Sweden with two laminates, pre-stressing force of 100 kN in each laminate.

Figure 7. Strengthening of The Gruvvagen bridge in Sweden with three laminates, pre-stressing force of 110 kN in each laminate.

The third project was performed in a hotel building in which different vertical segments of a wall were supposed to be pre-stressed all over the height. According to the calculations a pre-stressing force of 240 kN in total was needed. Four laminates, two on each side of the wall, were pre-stressed with a force of 65 kN to provide the amount of needed pre-stressing. Figure 8 shows the laminates mounted on the wall.

Figure 8. Strengthening of a wall in a hotel building in Sweden with four laminates, pre-stressing force of 65 kN in each laminate.

VI. Conclusion remarks

A new method and a pre-stressing device for application of pre-stressed FRP laminates to structural members were introduced. The new method eliminates the need for mechanical anchorage of the laminates which offers several advantages compared to traditional methods using anchor plates including, (1) ease of application and less time consumption, (2) better durability and no risk of galvanic corrosion, (3) better inspectability and (4) lower cost.

The magnitude of the interfacial stresses along the bond line in the adhesive layer could be controlled by changing the number of steps, i.e. tabs, in this method. By using ten tabs, pre-stressing forces up to 110 kN, ca. 43% of ultimate strength of CFRP laminates used in this study have been applied in practice.

The experimental work and field applications performed using this technique proved that rather high pre-stressing forces could safely be applied to the FRP laminates without any need for mechanical anchorage. The amount of measures loss in pre-stressing force after the release was about 1% of the total pre-stressing force.

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