Prestressed shear strengthening of a box girder bridge with non-laminated CFRP straps

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ABSTRACT: The paper presents a preliminary feasibility study about the use of thermoplastic, non-laminated CFRP straps for the shear strengthening of a box girder bridge. A bridge in Switzerland, which was strengthened against shear with conventional steel strands, was considered as an example. The principle idea of the strengthening method is to wrap prefabricated CFRP tendons made of these straps around the web. The CFRP tendons are connected and prestressed at the inside of the box girder also with CFRP tendons. They are applied without bond so that, theoretically, they can be re-adjusted during the lifetime of the structure. At the corners of the web, round prefabricated high-strength concrete elements are applied in order to ensure a proper force transfer. Besides the description of the bridge which was used for the study, the CFRP tendons and the principal construction process, friction tests on small scale CFRP tendons with different packaging materials are described.

1 INTRODUCTION

Strengthening techniques for civil structures using carbon fiber reinforced polymer (CFRP) have different advantages, such as being significant lighter and easier to handle compared to steel. Usually, the CFRP strips or fabrics are bonded onto the concrete surface. Strengthening methods include flexural, shear and torsional strengthening as well as confinement. However, in this paper, a new method for prestressed shear strengthening using FRP without bond is presented.

The prestressing of a shear strengthening has several advantages:
- higher crack and failure loads, higher deformations at failure, Marti et al. (1992),
- width of existing shear cracks can be reduced,
- existing stresses in internal steel stirrups can be reduced,
- immediately reaction to additional loads,
- better utilization of the strengthening material.

Furthermore, in Switzerland it is regulated (according to the Swisscode, SIA166 (2004) that, if a beam with shear cracks has to be strengthened for shear, stirrups should be used which can be wrapped around the whole beam height and which can be prestressed.

In the paper, a preliminary feasibility study is presented on the possible use of CFRP tendons for shear strengthening of a box girder bridge. The idea is, that the CFRP tendons are wrapped around the web without any bonding and then prestressed. Consequently, this means that they are not bonded onto the concrete.

The CFRP tendon shall be manufactured from multilayered thermoplastic CFRP straps, which were developed in a PhD work at Empa for tensile applications in civil engineering structures, winistörfzer (1999). In the meantime they are supplied by the Empa spin-off company Carbo-Link, (Carbo-Link).

In the framework of the PhD, winistörfzer (1999), a 3.35 m long RC beam was shear strengthened by using prestressed CFRP straps, Lees et al. (2002). The principal feasibility could be shown.
The feasibility of the system was also shown in another PhD work including large-scale tests at ETH Zurich, Stenger (2001). Furthermore, a research group from the University of Cambridge is also active in the field of prestressed shear strengthening of concrete by using CFRP straps. They have been working on several research projects in order to investigate the influence of the prestressed straps on the load bearing behavior of the beams, see e.g. (Kesse et al. 2007a; Kesse et al. 2007b; Hoult et al. 2007). In addition, they developed the so-called “under slap installation technique” which has the advantage that the shear strengthening can be applied without access to the top side of the beam so that the retrofitting work can be done without interrupting the traffic on the bridge.

The presented solution has several advantages compared to the existing conventional solution using steel strands, such as the fact that it has a considerably better aesthetic appearance. Furthermore, because the use of steel can be avoided, a superior durability is expected. Also, if required, tendons stress can be controlled and adjusted.

2 BOX GIRDER BRIDGE Z33A

In the presented investigation, the box girder bridge Z33A of the canton Solothurn in Switzerland, which was strengthened against shear with conventional steel strands, was considered as an example. The bridge Z33A was rehabilitated and strengthened in 1996-97.

In Figure 1 and Figure 2 the principle dimensions of the bridge in longitudinal view and cross-section are visible. In Figure 3 a drawing and in Figure 4 a photo from the shear strengthening is displayed. The shear strengthening of the webs was made with two steel strands with different spacing’s. The strands were redirected at the corners with steel saddles. A further strengthening, with the same spacing, was added at the compression plate of the box girder bridge. For the lower strands steel cantilevers were used, Figure 3 and Figure 4.

Figure 1: Longitudinal view of the bridge Z33A

Figure 2: Cross-section of the bridge Z33A

For the existing shear strengthening of one web with varying spacing’s of 0.5 m to 2 m the following assumptions, on the basis of the available documents of the structure, for cross-section, strength and prestressing were made:
• Cross-section of the strands \( A_p = 2 \times 150 \text{ mm}^2 = 300 \text{ mm}^2 \)
• Nominal yield strength \( f_{py} = 1590 \text{ N/mm}^2 \)
• Nominal tensile strength \( f_{pk} = 1770 \text{ N/mm}^2 \)
• Nominal force at start of yielding \( F_{py} = 477 \text{ kN} \)
• Nominal force at tensile failure \( F_{pk} = 531 \text{ kN} \)
• Prestress \( 70\% \ f_{pk} = 1239 \text{ N/mm}^2 \)
• Force corresponding to prestress \( = 372 \text{ kN} \)

Figure 3: Conventional shear strengthening, detail of the drawing

Figure 4: Photo of the steel strands, steel saddle and cantilever

3 CFRP TENDONS

Experiments and numerical modeling, Winistörfer (1999), have shown, that in laminated pin-loaded straps, as shown in Figure 5, severe stress concentrations are existing in the region where the straps and the pin meets, what reduces the tensile capacity of the system. A further disadvantage of laminated strap is the laborious production process.

Figure 5: Laminated CFRP straps, full bond between the layers
Figure 6: Carbo-Link (non-laminated CFRP straps), no bond between the layers
A novel design approach which diminishes the undesirable stress concentrations and overcomes the manufacturing difficulties are the non-laminated CFRP straps called Carbo-Link, see Figure 6. They are manufactured by wrapping thin straps around two pins and only the outermost layer is fusion bonded to the next outermost layer to form a closed loop.

The straps are produced in user-defined width up to 50 mm. The maximal number of the layers depends on the type of application and necessary package material. The straps consist of unidirectional carbon fibers in a thermoplastic matrix, which is for example Polyetherimid (PEI). The glass transition temperature of PEI is approximately 215°C. The fiber volume fraction is approximately 60%.

Different dimensions and elastic modulus of the single layers are used. This is the reason why only the total stiffness $EA$ of the CFRP tendons and corresponding width is stated. Additionally, the tensile capacity of the CFRP tendon is given.

4 PROPOSAL FOR PRESTRESSED SHEAR STRENGTHENING OF THE BOX GIRDER BRIDGE Z33A

4.1 Construction process

Figure 7 describes the proposed construction process. It can be seen that after removing the concrete and producing the holes, prefabricated high-strength concrete saddles are applied in order to ensure a proper force transfer. Concrete instead of steel is used for the saddles because of the better durability (corrosion). Then, the prefabricated CFRP tendons are wrapped around the web and prestressed at the inside of the box girder. The connection between the both ends of the tendon is also made with short non-laminated CFRP tendons, which are produced on site to the required length.

Figure 7: Construction process of the shear strengthening using CFRP tendons

4.2 Design of the CFRP tendons

For the design of the CFRP tendons the same forces with the same spacing’s like the existing steel version were used. Beside that, the concrete compression stresses at the saddles and the width limitation due to the production process influenced the geometry of the tendons:
- Nominal width of the straps: 2 x 35 mm
- Approximate thickness of the tendons including package material: 6.5 mm
- Stiffness EA: 2 x 18.5 MN
- Prestress force: 70% $F_L = 372$ kN
- Prestress force temporarily (overstressing): 75% $F_L = 398$ kN
- Failure force: $F_L = 531$ kN

4.3 Design of the concrete saddles

By using the equation

$$\sigma_c = \frac{F_L}{r \cdot b_L}$$  \hspace{1cm} (1)

with $\sigma_c =$ concrete compression stress, $F_L =$ force in the CFRP tendon, $r =$ radius of the concrete saddle and $b_L =$ width of the CFRP tendon, the concrete stresses were calculated. On the basis of that, a radius of 170 mm with a concrete type C75/90 was chosen for the saddles.

5 Friction Tests

Friction tests were performed in order to obtain the effect of friction and corresponding force losses at the corners. Three CFRP tendons with a width of 12 mm and stiffness EA of 13.5 MN with different package materials were tested in 90° and 180° friction tests, Figure 8 and Figure 9. The results are shown in Table 1. The presented values for the friction coefficient $\mu$ were determined with a 0.5 mm PTFE sheet between the concrete and the CFRP tendons.

<table>
<thead>
<tr>
<th>Type of package material of the CFRP tendons</th>
<th>Friction coefficient $\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black PVC shrink tube</td>
<td>0.02</td>
</tr>
<tr>
<td>Black PVC shrink tube and white PE braid</td>
<td>0.04</td>
</tr>
<tr>
<td>Black PVC shrink tube and PTFE CPS tape</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Table 1: Results of the friction tests

The friction loss can be calculated for a tendon with the package material black PVC shrink tube and white PE braid using following equation, e.g. from Gieck (1984)

$$F_2 = F_1 \cdot e^{-\mu \alpha}$$  \hspace{1cm} (2)

where $F_1 =$ force before the deviation, $F_2 =$ force after deviation, $\mu = 0.04$, $\alpha =$ deviation angle (180°) to 12%, what means that the prestressing force of 372 kN is reduced to 328 kN. With an overstressing force of 398 kN with subsequent releasing to 372 kN, a prestressing force on the other side of the web of 351 kN (6% prestress loss) results, what is judged as acceptable.

6 Conclusion and Outlook

CFRP tendons made of non-laminated CFRP straps can be used for prestressed shear strengthening of box girder bridges. However, prior to a first application, some detailed questions, have to be investigated. For example the load carrying behavior of the highly loaded concrete saddles has to be studied with tests. Furthermore, the prestressing procedure should be tried out in large scale tests. Last but not least, simplified models shall be developed for design purposes.
7 ACKNOWLEDGEMENT

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8 REFERENCES

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