Cracking of Beams Strengthened with Externally Bonded SRP Tapes

Rafał Krzywoń 1

1 Silesian University of Technology, Akademicka 5, 44-100 Gliwice, Poland
rafal.krzywon@polsl.pl

Abstract. Paper discusses strengthening efficiency of relatively new kind of SRP composite based on high strength steel wires. They are made of ultra-high strength steel primarily used in cords of car tires. Through advanced treatment, the mechanical properties of SRP steel are similar to other high carbon cold drawn steels used in construction industry. Strength significantly exceed 2000 MPa, there is no perfect plasticity at yield stress level. Almost linear stress-strain relationship makes SRP steel mechanical properties similar to carbon fibers. Also flexibility and weight ratio of the composite overlay is slightly worse than CFRP strip. Despite these advantages SRP is not as popular as other composites reinforced with fibers of high strength. This is due to the small number of studies of SRP behaviour and applicability. Paper shows selected results of the laboratory test of beams strengthened with use of SRP and CFRP externally bonded overlays. Attention has been focused primarily on the phenomenon of cracking. Comparison include the cracking moment, crack width and spacing, coverage of crack zone. Despite the somewhat lower rigidity of SRP tapes, they have a much better adhesion to concrete, so that the crack width is comparable in almost the whole load range. The paper also includes an assessment of the common methods of checking the condition of cracking in relation to the tested SRP strengthening. The paper presents actual calculation procedures to determine the crack spacing and crack width. The discussed formulas are verified with results of provided laboratory tests.

1. Introduction

Despite the popularity of externally bonded FRP strengthening systems RC members there is still few researches on the serviceability issues, especially when compared to the studies of carrying capacity or bond performance. In terms of cracking phenomena existing design guidelines contain a very simplified models or even ignore the problem. There is also few attempts to experimental verification of these recommendations.

The paper describes the issue of crack propagation in externally strengthened rectangular RC beams. Three types of externally bonded reinforcement were tested: CFRP sheets, strips and SRP tapes. Results of those investigations were compared with selected recommendations for longitudinal crack control. Possible reasons of differences between obtained laboratory measures and results of theoretical analyses are discussed in the conclusions with some recommendations for the necessary further investigations.
2. **Longitudinal cracking of FRP EBR strengthened beams**

Externally bonded strengthening has beneficial impact on cracking. It results from the tension stiffening phenomena, which appears not only at the steel-concrete interface, but also at the FRP-concrete interface. This effect can be called crack bridging and was proved in tests by Yoshizawa and Wu [1], Tripi et al. [2], Matthys [3] and Ceroni et al. [4]. Tension stiffening of external reinforcement reduces the crack spacing by forcing the formation of new cracks between the existing ones. Thanks to that phenomena crack width in RC elements strengthened with FRP is generally smaller than for unstrengthen elements. The second reason for better crack behaviour is greater flexural stiffness, which reduces beam’s deformation and thus tensile strain in the longitudinal crack zone, however, FRP materials have usually small cross-sectional area, and because of that, their effect on the reduction of deflection is relatively low (except very low reinforced sections).

Analysis of cracking resistance of externally strengthened beams should be provided on the same rules as typical RC elements. Stresses are calculated by using section properties corresponding to full cracking. Concrete, steel and FRP reinforcement are considered as linear elastic. Calculation of stresses is provided on the basis of internal and external forces equilibria, with the only difference of taking into account the external strengthening.

Eurocode 2 [5] suggest following formulation to calculate the crack width:

\[ w_k = \frac{s_{r,\text{max}} \cdot (\varepsilon_{\text{on}} - \varepsilon_{\text{mc}})}{1} \]  

where \( s_{r,\text{max}} \) means the maximum crack spacing equal to:

\[ s_{r,\text{max}} = k_3 \cdot c + k_1 \cdot k_2 \cdot k_4 \cdot \frac{\phi}{\rho_{\text{eff,eq}}} \]  

\( k_1 \) takes account of the bond properties, for high bond bars \( k_1 = 0.8 \); \( k_2 \) takes account of the distribution strain, for bending \( k_2 = 0.5 \); \( k_3 = 3.4 \); \( k_4 = 0.425 \); \( \phi \) is the bar diameter and \( c \) is cover.

The percentage of present externally bonded reinforcement could be considered as:

\[ \rho_{\text{eff,eq}} = \rho_{\text{p,eff}} + \rho_{\text{f,eff,eq}} = \frac{A_s + A_f \cdot \frac{E_f}{E_s}}{A_{c,\text{eff}}} \]  

where \( E_s \) and \( E_f \) are Young’s modules of steel and externally bonded reinforcement, \( A_s \) and \( A_f \) are the areas of provided steel and strengthening, \( A_{c,\text{eff}} \) is the effective tension area (figure 1):

![Figure 1. Effective tension area for beam according to Eurocode [5]](image)
\((\varepsilon_{sm} - \varepsilon_{cm})\) is the difference of the mean strain of steel to the concrete between cracks. Considering the externally bonded reinforcement, it could be calculated as follows:

\[
\varepsilon_{sm} - \varepsilon_{cm} = \frac{\sigma_s}{E_s} \left( -k_t \left[ \frac{f_{cm}}{E_s \cdot \rho_{eff,eq}} + \frac{f_{cm}}{E_{cm}} \right] \right)
\]

(4)

where \(E_{cm}\) is the mean Young module of concrete, \(f_{cm}\) is the mean tensile strength of concrete, \(\sigma_s\) is stress in the tension reinforcement assuming a cracked section and \(k_t\) takes account of load duration.

Another approach, based on the Model Code 90 [6] provisions and Rostasy [7] is proposed in fib bulletin 14 [8]. Crack spacing taking account the external reinforcement is equal:

\[
s_{rm} = \frac{2 \cdot f_{cm} A_{c,eff}}{\tau_{fm} u_f + \tau_{sm} u_s}
\]

(5)

where \(\tau_{fm} = 1.25f_{cm}\), \(\tau_{sm} = 1.8f_{cm}\); \(u_f\) is the bond width of EBR reinforcement \((u_f = b_f)\), \(u_s\) is the bond perimeter of steel bars \((u_s = n \cdot \pi \cdot \phi)\).

The maximum crack spacing could be found as follows:

\[
s_{r, max} = \beta \cdot s_{rm} = 1.7s_{rm}
\]

(6)

Presented models are based on modifications developed initially for classic concrete structures with internal reinforcement. Original approach for FRP strengthened beams, based on test results, was proposed by Ceroni and Pecce [9]. Considering the experimental database, calibrated formula for crack spacing takes a form:

\[
s_{rm} = 20 + \frac{4 \cdot A_{c,eff}^{0.5} \cdot \phi}{A_s^{0.75} + \left( A_f \frac{E_f}{E_s} \right)^{0.75}} \text{ [mm]}
\]

(7)

\(A_{c,eff}, A_s, A_f\) given in mm. Assuming the 95th percentile distribution of crack spacing, maximum crack width could be assumed:

\[
s_{r, max} = s_{rm,95\%} = 1.55s_{rm}
\]

(8)

3. Laboratory tests

17 full scale RC beams strengthened using SRP tapes and CFRP strips were investigated in four point bending test shown in figure 2. In details test included:

- one reference unstrengthen beam,
- 7 beams strengthened using SRP 3X2-20 in one layer (five of them overwrapped in the anchorage zone), 150mm wide,
- 4 beams strengthened using 2 layers of SRP 3X2-12 tape (two of them overwrapped in the anchorage zone), each 150mm wide,
- 3 beams strengthened with CFRP strips overwrapped in the anchorage zone, tape S&P CFK 200/2000 strips 60x1.4mm,
2 beams strengthened with CFRP high modular sheet overwrapped in the anchorage zone, S&P CFRP carbon sheet 640-400, 150mm wide.

Specimens have been made on the basis of this same concrete mixture. The mean cube compressive strength of concrete was 44.7 MPa, the mean tensile strength of concrete estimated from the Brazilian probe 3.2 MPa and the mean concrete modulus of elasticity 30.4 GPa. All the specimens were reinforced with three Ø12 bottom ribbed bars (yield strength 570 MPa) and two Ø8 top ribbed bars (yield strength 588 MPa).

In accordance with the recommendations of the manufacturers of the strengthening systems to adhere the CFRP strips S & P Resin 220 was used and Sikadur 330 for the impregnation of the SRP tape (due to the high density of strands tape SRP require the use of products with a viscosity intermediate between the conventional adhesives and resins). In addition, the day before the application of external strengthening beams were impregnated with the S & P Resin 55.

![Figure 2. Test lay-out](image)

![Figure 3. Tested externally bonded reinforcement: a) CFRP strip; b) CFRP sheet; c) SRP tape](image)

Experimental program was aimed at evaluating the effect of SRP and CFRP types of external flexural strengthening on RC beams. Among the analysed issues were strengthening effectiveness
4. Test results and discussion
Beams were tested to failure. For a load level of every 0.5 kNm crack pattern was mapped (figure 4) and width of main cracks was measured.

![Figure 4. Development of crack pattern](image)

The appearance of first crack was observed around load level causing bending moment equal to 13÷15 kNm. There was no visible impact of applied external reinforcement on the value of cracking
moment. This can be explained by the effect of relatively small stiffness of externally bonded strengthening in relation to the whole, not cracked beam.

Table 1 presents measured maximum crack spacing and table 2 average crack spacing along the length of constant bending at 40 and 50 kNm. Such a load level was chosen as corresponding with service load of approximately 70% of ultimate resistance. As can be found, in general application of external reinforcement provides to better crack distribution. Maximum and average crack spacing for all types of strengthening is lower than observed for reference not-strengthened beam. Crack pattern is the most uniform for beams strengthened with a single layer of SRP 3X2-20. Average crack spacing is the lowest for this type of strengthening and maximum spacing only slightly ranks after two layers of 3X2-12. This is despite of the lowest equivalent stiffness of SRP in comparison to CFRP strips and sheets. Phenomenon of better cracks distribution and their smaller spacing was also reported by Ceroni and Pecce [13] and Balsamo et al [14].

Mentioned tables are also showing the comparison of experimental and theoretical crack spacing based on code recommendations. As can be observed, generally EC2 and \textit{fib}14 formulations overestimate the experimental results. The exception is high-modulus CFRP sheet, where crack spacing is significantly underestimated. This could be the effect of uncommon modulus of elasticity and mismatches of code formulas for such a type of strengthening material. Interestingly, closest are results obtained for SRP beams. Especially Ceroni [9] method seems to be ideally fitted for SRP beams, however, it should be noted, that this method was partly calibrated on test results of SRP 3X2 and 12X tapes.

| Model | Beam strengthening | Experimental crack spacing [mm] | Theoretical crack spacing [mm] |
|-------|--------------------|-------------------------------|-------------------------------|
|       | at 40kNm at 50kNm average | EC2 [5] | \textit{fib}14 [8] | Ceroni [9] |
| BWZ   | Reference (no strengthening) | 147 | 147 | 147 | 164 | - | - |
| FRO1  | CFRP strip 60x1.4mm | 129 | 129 | 134 | 145 | 195 | 119 |
| FRO2  | 163 | 138 | 111 | 111 | 111 | 111 |
| FRO3  | CFRP sheet two layers 200mm wide | 142 | 142 | 139 | 125 | 119 | 99 |
| FRS1  | 136 | 136 | 123 | 148 | 139 | 123 |
| FRS2  | 136 | 136 | 123 | 148 | 139 | 123 |
| SRP1  | 144 | 144 | 144 | 144 | 144 | 144 |
| SRP2  | 117 | 117 | 117 | 117 | 117 | 117 |
| SRO1  | SRP tape type 3x2-20 one layer | 109 | 90 | 90 | 90 | 90 |
| SRO2  | 140 | 140 | 123 | 150 | 139 | 125 |
| SRO3  | 96 | 96 | 96 | 96 | 96 | 96 |
| SRO4  | 109 | 109 | 109 | 109 | 109 | 109 |
| SRO5  | 147 | 93 | 147 | 93 | 147 | 93 |
| SROP1 | SRP tape type 3x2-20 one layer | 123 | 123 | 123 | 123 | 123 | 123 |
| SROP2 | 133 | 113 | 133 | 113 | 133 | 113 |
| SROP3 | 128 | 99 | 128 | 99 | 128 | 99 |
| SROP4 | 101 | 101 | 101 | 101 | 101 | 101 |

* Crack spacing referred to type of strengthening at bending moment equal to 40kNm.

Despite the greater deformability (lower stiffness) of SRP beams, better distribution of cracks caused that crack widths of all beams were similar for all investigated load levels. Initially, at load level causing the yield of internal reinforcement, appearance of new cracks was observed and further, accelerated opening of existing cracks.
5. Conclusions

The described tests of cracking behaviour of RC beams externally strengthened with composite materials lead to following conclusions:

- External strengthening significantly reduces the crack spacing and crack widths. This is due to the additional tension stiffening effect provided by the external composite material bonded to the bottom surface.

| Model | Beam strengthening | Experimental crack spacing [mm] | Theoretical crack spacing [mm] |
|-------|--------------------|---------------------------------|--------------------------------|
| BWZ   | Reference (no strengthening)  | 107 | 107 | 95 | 95 | 77 | 115 | 77 |
| FRO1  | CFRP strip 60x1.4mm | 88 | 88 |
| FRO2  | CFRP sheet two layers 200mm wide | 92 | 92 |
| FRO3  | | 79 | 74 |
| FRS1  | | 92 | 92 |
| FRS2  | | 105 | 98 | 91 | 70 | 64 |
| SRP1  | | 95 | 95 |
| SRP2  | | 79 | 65 |
| SRO1  | SRP tape type 3x2-20 one layer 150mm wide | 96 | 82 | 86 | 73 | 82 | 81 |
| SRO2  | | 66 | 66 |
| SRO3  | | 75 | 71 |
| SRO4  | | 82 | 63 |
| SRO5  | | 89 | 89 |
| SROP1 | SRP tape type 3x2-20 one layer 150mm wide | 85 | 85 | 77 |
| SROP2 | | 94 | 94 | 84 | 82 | 82 | 79 |
| SROP3 | | 76 | 76 |
| SROP4 | | | |

\(^a^\) Crack spacing referred to type of strengthening at bending moment equal to 40kNm.

\(^b^\) Crack spacing referred to type of strengthening at bending moment equal to 50kNm.

- Carried out researches have not confirmed the effect of the growing equivalent reinforcement ratio on reduction of crack spacing. More important is the contact (bond) surface between reinforcement and concrete. It is considered by \(\text{fib}14\) [8] model and omitted in EC2 [5] procedure. Eventual further modification of EC2 formulations needs study this aspect.

- Best crack evaluation allows Ceroni and Piece method [9]. It is calibrated on large experimental database of externally strengthened elements.

- Tests proved, that SRP reinforcement type can be very competitive to other externally bonded strengthenings also in terms of crack resistance. Thanks to its wider width it exhibits better ability of crack bridging. Crack distribution is more uniform and their width is lower.

Acknowledgment(s)

Research program was supported by the National Science Centre of Poland, grant no 1231/B/T02/2011/40.
References

[1] H. Yoshizawa, Z. Wu, “Crack Behavior of Plain Concrete and Reinforced Concrete Members Strengthened with Carbon Fiber Sheets,” *Proceedings of Fourth International Symposium on FRP Reinforcement*, vol. 1, pp. 767-779, 1999.

[2] J. M. Trippi, C. E. Bakis, T. E. Boothby, and A. Nanni, “Deformation in concrete with external CFRP sheet reinforcement,” *ASCE Journal of Composites for Construction*, vol. 4, no. 2, pp. 85-94, 2000.

[3] S. Matthys, “Structural behaviour and design of concrete members strengthened with externally bonded FRP reinforcement,” PhD thesis, Faculty of Engineering, Department of Structural Engineering, Ghent University, Belgium, 2000.

[4] F. Ceroni, M. Pecce, S. Matthys, “Tension Stiffening of RC Ties Strengthened with Externally Bonded FRP Sheets,” *ASCE Journal of Composites for Construction*, vol. 8, no. 1, pp. 22-32, 2004.

[5] Eurocode 2, “Design of concrete structures – Part 1: General rules and rules for buildings,” EN 1992-1-1, 2004.

[6] CEB-FIP Model Code 1990, Design Code, Comite Euro-International Beton, Lausanne, Switzerland, 1993.

[7] F. S. Rostasy, P. Holzenkampfer, C. Hankers, “Geklebte Bewehrung für die Verstärkung von Betonbauteilen,” *Betonkalender*, vol. 2, pp. 547-576, 1996.

[8] FIB bulletin No. 14, “Externally bonded FRP reinforcement for RC structures,” International Federation for Structural Concrete, Lausanne, Switzerland 2001.

[9] F. Ceroni, M. Pecce, “Evaluation of crack spacing in RC elements externally bonded with FRP,” *Fourth International Conference on FRP composites in Civil Engineering (CICE2008)*, pp. 1–6, 2008.

[10] R. Krzywon, “Effectiveness of SRP flexural strengthening compared to CFRP strips,” *ACEE Architecture Civil Engineering Environment*, vol. 8, no. 4, pp. 39-44, 2015.

[11] R. Krzywon, S. Dawczynski, M. Gorski, “Long-term comparative tests of RC beams strengthened with CFRP strip and SRP tape,” *Proceedings of the International Conference on Engineering ICEUBI2015 Engineering for Society*, Covilha, Portugal, pp 1-7, 2015.

[12] R. Krzywon, M. Gorski, S. Dawczynski, “Features of SRP tapes against CFRP composites used for strengthening of concrete structures,” *Proceedia Engineering, Proceedings of the International Conference on Analytical Models and New Concepts in Concrete and Masonry Structures*, pp 1-8, 2017.

[13] F. Ceroni, M. Pecce, “Cracking behavior of RC beams externally strengthened with emerging materials,” *Construction Building Materials*, 21(4), pp.736–45, 2007.

[14] A. Balsamo, F. Nardone, I. Iovinella, F. Ceroni, M. Pecce, “Flexural strengthening of concrete beams with EB-FRP, SRP and SRCM: Experimental investigation,” *Composites: Part B*, 46, pp. 91–101, 2013.