EFFECTIVENESS OF SRP FLEXURAL STRENGTHENING COMPARED TO CFRP STRIPS

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Abstract

SRP composites are based on ultra-high strength steel wires formed in cords and assembled into a fabric. Properties of the steel used in the production of wires are similar to other high carbon cold drawn steels (for example prestressing steel): there is no perfect plasticity at yield stress level. Almost linear stress-strain relationship makes them comparable to Carbon FRP polymers. Also flexibility and weight ratio of the composite overlay is similar to FRP strips rather than flat bars made of ordinary steel. In view of those similarities SRP composites are treated and designed with use of well-known procedures developed for CFRPs. The paper provides a discussion of the comparative laboratory test of dozen beams strengthened with the use of SRP and CFRP materials.

Streszczenie

Kompozyty SRP są zbrojone drutami ze stali o wysokiej wytrzymałości w formie splotów, które łączy się poprzecznie tworząc rodzaj maty. Właściwości mechaniczne stali wykorzystywanej do produkcji drutów są podobne do innych wysokowęglowych stali wytwarzanych w procesie obróbki plastycznej na zimno (np. stali do sprężania): nie występuje w nich płynięcie półka plastyczna. Prawie liniowa zależność naprężenie – odkształcenie upodabnia kompozyty SRP do laminatów zbrojonych włóknem węglowym. Podobnie pod względem łatwości kształtowania i ciężaru własnego, bardziej odpowiadają one taśmom węglowym niż stalowym płaskownikom. Z uwagi na te podobieństwa zasady projektowania i stosowania wzmocnień na zginanie, bazują na dobrze znanych procedurach do projektowania tego typu wzmocnień przy użyciu taśm CFRP. W artykule przedstawiono wyniki testów porównawczych kilkunastu belek wzmocnionych taśmami typu SRP i CFRP.

Keywords: **FRP Strengthening; Steel Reinforced Polymers; UHTS steel.**

1. INTRODUCTION

Composites based on organic high strength fibers have been successively replacing structural steel in construction, especially in the field of external strengthening of structures. In our times market offers a wide range of fibers with different mechanical properties and price. Most commonly used are carbon fibers, but it is not always necessary to use the most expensive product, especially when similar properties can also be offered by modern steel.

Based on ultra-high tensile strength steel (UHTS) wires, SRP (Steel Reinforced Polymer) and SRG (Steel Reinforced Grout) tapes are representing a relatively new material which can be used as reinforcement of composite. Used in production, steel wires are made of the same perlite steel as used for making the reinforcement of automotive tires. As a consequence of the drawing process, a small diameter, smooth surface do not allows for good bond properties, but, twisting of wires (similarly to prestressing tendons) into the

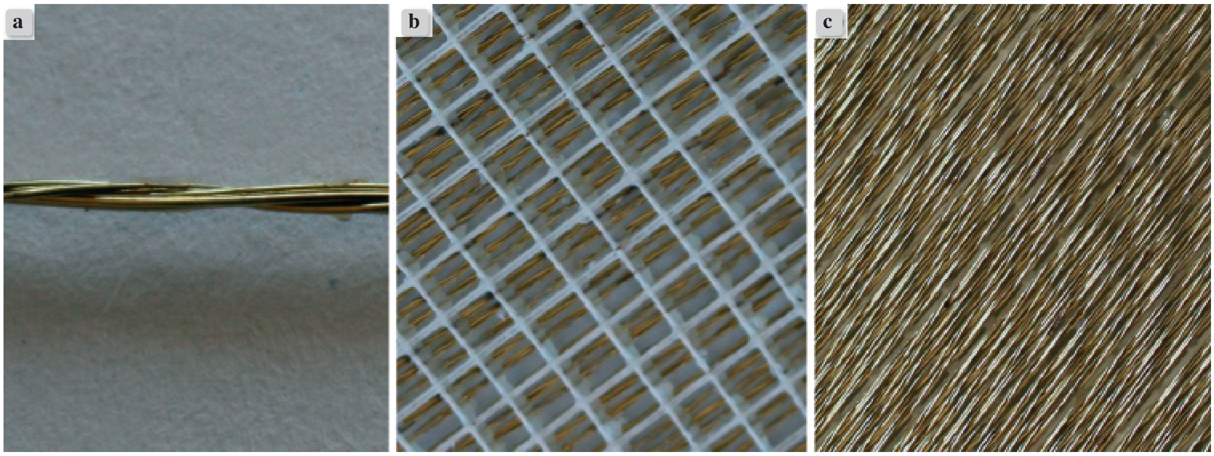

Figure 1.
The most popular 3x2 cord type and SRP tapes with various densities (private collection)

strands (Fig. 1a) creates mechanical interlock between concrete and steel and additionally integrates filaments. The negative effect of this treatment is slight deterioration of mechanical properties. In the next step of the manufacture process, unidirectional tendons are joined into a fabric by knitting in the transverse yarns based on glass fibers (Fig. 1b, 1c). Density of the cords (number of cords per centimeter of width), can be adjusted to the required fabric parameters. Linked fabric can be also stretched or bent, without losing its integrity, which is particularly important during installation. Filaments in actually produced fabrics are spaced up to 6mm in light, what allows the use of a wide range of matrices with different viscosity: from high viscosity epoxy resins to the cementitious mixtures.

2. PROPERTIES OF THE UHTS STEEL AND SRP/SRG TAPES

Ultra-High Tensile Steel is about 5 times stronger than normal one. So good mechanical properties are obtained by proper selection of chemical composition, heat and mechanical treatment allowing to build the crystal structure of pearlitic steel. The carbon content of steels of this type is in the range of 0.8-0.96%. Steel in the form of wire is treated by drawing to a diameter of 0.20-0.35 mm. During this process the grains or single crystals of pearlitic steel in the structure are aligned in the direction of drawing, along the wire. By controlling the distance of the plates of the perlite it is possible to increase the draw tension and consequently a better arrangement of the plates. Thin plates of cementite in steel ensure its improved plastic deformability. The capability of strain hardening of this type of eutectoid steel is greater than the low-carbon steel. Such steels have both high strength and good ductility.

2.1. Mechanical properties

As the most of FRP reinforcing materials, also SRP composites have an excellent tensile strength in the direction of the filaments and negligible strength in the transverse direction. It is the result of a one-way arrangement of steel cords, transverse properties are mainly provided by the polymeric matrix and additionally glass fibers of knitting yarns. It means that the arrangement of the fabric should be aligned to the direction of principal stresses in the structure.

Theoretically the strength of the iron crystals is estimated to reach 10000-13000 MPa. Today, drawing technology allows to get the structural pearlitic steel of strengths up to 6000 MPa for wires with diameters of 40 microns. Wires used in the production of SRP fabrics have a diameter of 2 mm and strength of up to 3500 MPa. UHTS steel is also more ductile than other “traditional” organic composites. Comparing the mechanical properties (Table 1) it can be stated that the UHTS steel rival carbon fibers is significantly better than the glass and aramid fibers.

As well as other high-strength steel ductility is not comparable with conventional steels, however, it is much better than most of the composites reinforced with high-strength organic fibers. In addition, used steel fibers are continuous, so that there are no special requirements for quality of matrix, whose main role, apart from ensuring adherence to the reinforced element, is to protect the fibers from the external factors. The matrix does not need to be transferred the

Table 1.
Mechanical properties of strengthening materials

Material	Density (kg/m^3)	Modulus of elasticity E (GPa)	Tensile strength f_u (MPa)	Ultimate strain ε_u (%)
Mild steel	7850	200	500-650	>10
GFRP [1]	2600	30-60	400-1600	1.2-3.7
CFRP [1]	1800	80-500	600-3500	0.5-1.8
AFRP [1]	1400	30-125	600-2500	1.8-4.0
SRP	1500-5000	140-205	3300	1.7-3.0

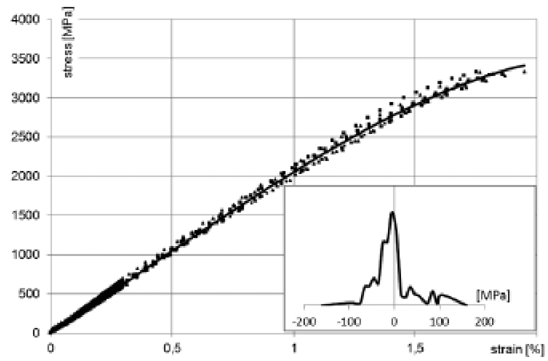

Figure 2.
Stress-strain relationship of SRP composite [2]

shear forces between the fibers, so it is possible to use a relatively large spacing of strands.

Table 1 shows properties of SRP composites in comparison with traditional steel and FRP composites.

Figure 2 illustrates tensile test results of six SRP specimens made of fabrics with two densities (5 and 8 cords/cm) based on the most popular 3X2 cord type. As can be seen, stress – strain relationship is nearly linear in the range of 80% of total strength, there is no visible yield level and only a slight weakening appears just below the rupture level. As the author pointed out in the study [2] in most cases simplification of the nonlinear relationship by constant modulus of elasticity, equal of 200 GPa only slightly worsens the accuracy of the design models.

2.2. Effectiveness of application in construction strengthening

Efficiency of SRP strengthening in terms of capacity has been confirmed in many experimental tests. In the bending tests of *Mitolidis et al*. [3], flexural strengthening of R/C beams with SRP strips allowed to increase the loading capacity by 90% for specimens compared to the unstrengthened one. Slightly smaller effect reached *Wobbe et al.* [4] and *Ceroni et al.* [5], where strengthening efficiency reached the level of 70% and Huang et al. [6], who noticed the strength increase of about 30%.

Less impressive results were achieved in enhancing the deflection capacity. *Mitolidis et al*. [3] noticed just 17% reduction of deflection, *Ceroni et al.* [5] did not find any advantageous effect, deflections were similar to those recorded for the unstrengthened beams. Better results can be achieved only by prestressing of SRP tapes. *Balsamo et al*. [7] achieved more than 20% reduction of the ultimate load, but the effect is much more spectacular for service load levels, when deflection of unstrengthened and cracked beam growths far more rapidly.

Another important aspect in terms of the cost and easiness of application is the weight of the tapes. Composites based on steel wires are, depending on filaments density, up to five times lighter than steel. Those advantages are creating possibilities of wide range of applications in practice. Nowadays SRP laminates are used for strengthening slabs, beams, ring beams, columns, and nodes in frame structures, walls, and wall panels.

3. TEST RESULTS

The article reports comparative tests on 15 full scale RC beams strengthened using SRP tapes and CFRP strips. Compared parameters were capacity, total deflection, cracking ability and debonding strain. In details test included:

- one reference unstrengthened beam,
- 7 beams strengthened using SRP 3X2-20 in one layer (five of them overwrapped in the anchorage zone), 150 mm wide, of the theoretical tensile force corresponding to tensile strength 154.8 kN,
- 4 beams strengthened using 2 layers of SRP 3X2-12 tape (two of them overwrapped in the anchorage zone), 150 mm wide, of the theoretical tensile force corresponding to tensile strength 190.6 kN,
- 3 beams strengthened with CFRP strips overwrapped in the anchorage zone, tape S & P CFK 200/2000 strips 60×1.4 mm of theoretical tensile force corresponding to tensile strength 216.4 kN.

All the beams were tested in four point bending showed in Fig. 3.

Specimens have been made on the basis of this same concrete mixture. The mean cube compressive strength of concrete was 44.7 MPa, and the tensile strength of concrete estimated from the Brazilian probe had a mean value of 3.2 MPa. All the specimens were reinforced with three Ø12 bottom ribbed bars

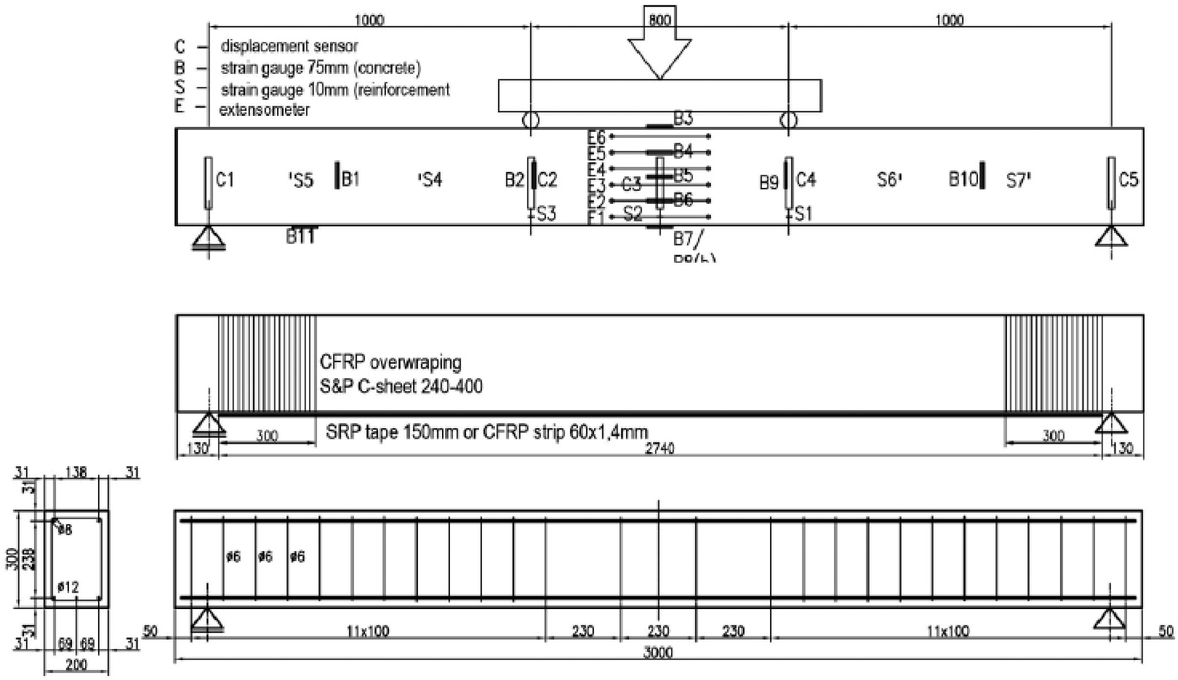

Figure 3.
Details of the specimens (test scheme, reinforcement)

(f_y = 570.1 MPa, f_u = 660.8 MPa at 11%) and two Ø8 top ribbed bars (f_y = 588.2 MPa, f_u = 635.4 MPa at 8%).

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 beams were impregnated with the S & P Resin 55.

3.1. Effectiveness of strengthening

The main results are summarized in Table 2 reporting the failure force, cracking force, maximum deflection, the strain of the composite in the zone of maximum bending moment and support zone (debonding strain).

The moment-deflection curves are reported in Fig. 4 for one representative beam of each series.

The experimental tests evidenced the good effectiveness of both CFRP strips and SRP tapes. All strengthened beams achieved relevant flexural strength increase compared with the reference one. In particular, the beams strengthened with CFRP strips attained the mean load increasing by about 43%, while the beams with one layer of SRP fabrics had a load increasing variable in the range 48-52% (not overwrapped and overwrapped, respectively). Best performance was observed for beams strengthened with two layers of SRP 3X2-12 (average 57%), while this type of strengthening was characterized by a very large dispersion of results (from 47% to 70%). It is probably the effect of large thickness of the laminate and the associated problems with providing adequate adhesion to the concrete. One specimen (SROP1) failed by delamination of the outer layer of the laminate. Typically, delamination started near the zone weakened by flexural crack, while in this single case, it was initiated in the anchoring zone by the end shear stresses. This confirms the suspicions about difficulty to ensure proper adhesion of the laminate with increased thickness. A more detailed description of the most common process of failure is given in Section 3.2.

3.2. Failure model

There was no beneficial effect of overwrapping of anchoring zone. Analyzing the failure mode should be noted that almost all of the specimens (except the described above SROP1) were destroyed in delamination initiated in the area constant bending

Table 2.
Selected test results

No	Specimen	Type of strengthening	Overwrap	Failure load [kN]	Load at cracking [kN]	Max deflection [mm]	Midspan strain [‰]	Anchorage strain [‰]
1	BWZ	no	-	99.2	25	85.2	-	-
2	FRO1	CFK 60×1.4	yes	145	27	20.55	5.828	1.721
3	FRO2	CFK 60×1.4	yes	139.7	27	20.22	5.328	1.811
4	FRO3*	CFK 60×1.4	yes	125	27	14.61	3.618	0.566
5	SRP1	SRP 3X2-20	no	150.5	27	27.43	7.659	1.057
6	SRP2	SRP 3X2-20	no	152.7	27	29.19	7.814	-
7	SRO1	SRP 3X2-20	yes	146.2	27	27.10	7.688	1.669
8	SRO2	SRP 3X2-20	yes	147	27	27.71	**	1.576
9	SRO3	SRP 3X2-20	yes	147.1	27	31.7	8.39	0.649
10	SRO4	SRP 3X2-20	yes	148.6	27	30.5	7.43	0.128
10	SRO5	SRP 3X2-20	yes	145.4	27	33.6	7.59	1.756
12	SROP1	2× SRP 3X2-12	no	149.8	28	23.84	6.30	0.118
13	SROP2	2× SRP 3X2-12	no	167.7	30	31.05	6.29	-
14	SROP3	2× SRP 3X2-12	yes	169.1	30	32.34	8.63	0.205
15	SROP4	2× SRP 3X2-12	yes	146.6	30	25.91	6.60	0.131

* premature failure due to defects of bond layer, ** sensor failure

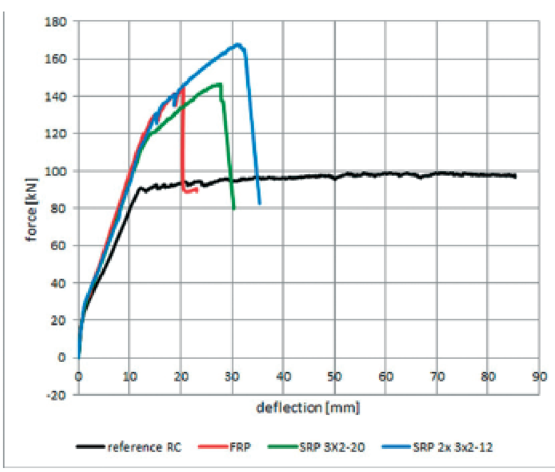

Figure 4.
Load-deflection curves for representative specimens

Figure 5.
Detachment of the overwrapping sheet (private collection)

(midspan zone). Delamination running from the center towards the supports caused separation of the bottom part of overwrapping. This type of delamination is due to the inequality of strains across the perpendicular crack. Stiffness of the CFRP laminate across the fibers is relatively small, so it could not realize its anchoring role. Finally delamination reaches the end of laminate and provides to detachment of overwrapping, which is shown in the Fig. 5.

For all models, strengthened with CFRP strips, delamination occurred in the adhesive, while all models of SRP were destroyed after the delamination in the surrounding concrete. All surfaces before application of the laminate were prepared in the same way – S&P Resin 55 impregnation. It is therefore conceivable that the observed delamination model is the result of improper surface preparation for CFRP strips. The most likely cause of this phenomenon is more than twice the area of contact SRP tape so that shear stress in the adhesive can be significantly reduced.

In general, the failure load of beams strengthened with SRP was slightly higher compared with the beams strengthened with CFRP strips, despite of relatively lower bearing capacity. Analyzing the change in strain of the composite should be noted that in the case of tape SRP and CFRP strips are very similar, but CFRP strip delamination occurs more rapidly. This observation is contrary to the majority of already reported tests (similar results in part of the study received only *Minaugh* [8]). It should be emphasized, however, that most of these investigations compared the CFRP laminate adhesion rather than tapes.

The received delamination strain in the SRP strengthened beams was greater than 6‰, and up to 8‰. These values are consistent with the *Wobbe* [4] and *Balsamo* [7] studies, any differences may result from the form of delamination – debonding resistance of midspan zone is generally up to 3 times higher than strip anchoring [9]. The largest measured strain in the anchoring zone was 1.67‰.

For all the strengthened beams, cracking starts forming when the maximum moment is in the range 14-15 kNm. There is no visible difference in the cracking load observed for the beams strengthened with CFRP and SRP overlays.

In comparison to reference specimen external strengthening allows twice reduction of the deflection. This result should be considered as very promising especially when compared to the degree of reinforcement (0.12% for SRP and 0.57% for conventional steel).

For all the strengthened beams, the external reinforcement allowed to delay the yielding of the internal steel reinforcement. Visible in Fig. 4 change of the slope of stress strain relationship starts from 110 kN.

After cracking, the beams strengthened with CFRP strips showed a stiffer behavior compared with beams reinforced with SRP tapes due to the higher axial stiffness of the former ones. The consequence of this difference is a greater deflection at the beams failure.

4. CONCLUSIONS

Paper shows selected results of the experimental bending tests of RC beams strengthened using SRP and CFRP composites. Strengthening system made of SRP showed competitive effectiveness to CFRP strips. Despite theoretically lower capacity of composite fibers total strengthening effect was similar or even better. This result was achieved due to the wider bonding area of SRP composite (60 mm and 150 mm for the CFRP and SRP tape respectively). The failure mode of the strengthened beams was due to the debonding started at this cracked constant bending zone and propagated to the supports. There was no beneficial effect of overwrapping of anchoring zones of strengthening. External reinforcement slightly reduces deflection and a little growth of the cracking moment can also be observed.

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