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Experimental Studies of Sigma Thin-Walled Beams Strengthen by CFRP Tapes

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Abstract**—**The review of selected methods of strengthening of steel structures with carbon fiber reinforced polymer (CFRP) tapes and the analysis of influence of composite materials on the steel thin-walled elements are performed in this paper. The study is also focused to the problem of applying fast and effective strengthening methods of the steel structures made of thin-walled profiles. It is worth noting that the issue of strengthening the thin-walled structures is a very complex, due to inability to perform welded joints in this type of elements and the limited ability to applying mechanical fasteners. Moreover, structures made of thin-walled cross-section demonstrate a high sensitivity to imperfections and tendency to interactive buckling, which may substantially contribute to the reduction of critical load capacity. Due to the lack of commonly used and recognized modern methods of strengthening of thin-walled steel structures, authors performed the experimental studies of thin-walled sigma profiles strengthened with CFRP tapes. The paper presents the experimental stand and the preliminary results of laboratory test concerning the analysis of the effectiveness of the strengthening steel beams made of thin-walled sigma profiles with CFRP tapes. The study includes six beams made of the cold-rolled sigma profiles with height of 140 mm, wall thickness of 2.5 mm, and a length of 3 m, subjected to the uniformly distributed load. Four beams have been strengthened with carbon fiber tape Sika CarboDur S, while the other two were tested without strengthening to obtain reference results. Based on the obtained results, the evaluation of the accuracy of applied composite materials for strengthening of thin-walled structures was performed.

Keywords**—**CFRP tapes, sigma profiles, steel thin-walled structures, strengthening.

I. Introduction

THE thin-walled profiles have become attractive for designers of steel constructions and are increasingly used as secondary and main elements in of steel halls systems because of their large load capacity ratio with respect to the small weight.

Due to the possible design errors or the appearance of an unexpected load in the form of additional elements, e.g. ventilators or snowdrifts, there are sometimes necessity of strengthening the existing structure made of the thin-walled profiles. Inability to perform welded joints in this type of elements and the limited ability to applying mechanical fasteners caused strengthening them by composite materials (FRP - Fiber Reinforcement Polymers/Plastics). FRP tapes are materials which are based on non-metallic high strength fibers, embedded in an epoxy matrix. In building construction, there are used currently three types of composite materials, which differ in the type of fiber, namely CFRP, GFRP and AFRP (respectively carbon, glass and aramid). CFRP tapes are most commonly used composite materials for the strengthening of building structures. This follows from the excellent mechanical properties of carbon fibers in relation to the other materials. The main mechanical properties of CFRP composites are dependent on the type and the orientation of carbon fibers, the type and parameters of the epoxy resin, and its percentage in the final material. The main advantages of CFRP composite materials are following: over ten times higher strength in tension of the tape in fibers direction compared with conventional structural steel, a very high fatigue resistance, high durability due to high corrosion resistance, and lack of necessity of maintenance. Moreover, there is the possibility of strengthening with CFRP tape, structures made of various materials (concrete, steel, wood), with the ease and speed application, low labor cost, and easy transport. In constrast, the disadvantages are: low strength in compression, approximately 10% of the tensile strength and even smaller in case of interlaminar shear strength so called debonding. Furthermore, due to the brittleness and susceptibility to stress concentration, CFRP tape cannot be cut, drilled, or bended. Another disadvantage of these composite materials is the lack of resistance to high temperature due to the presence of epoxy resins. The maximum operating temperature of structures strengthen with CFRP tapes must not exceed 50 °C. In case of fire, this fact enforces additional fire protection in places strengthened with CFRP tapes. The application of CFRP strips to the steel bridge girders is widely discussed in literature, e.g. in [1], [2], but it is still deficiency of such references in case of thin-walled members. More recently, as an innovation, CFRP tapes have been used to improve the buckling and post-buckling behavior of steel thin-walled profiles. The effectiveness of application the FRP materials to provide improvements in the flange and web local buckling and flexural torsional buckling of steel members was investigated in [3]. In that paper, the possibility of stability improvement of cross-sectional to flange elements using small quantities of FRP tapes is discussed. It was assumed that this application is not aimed at increasing the load - carrying capacity of the steel section but at increasing the critical load of the member. The advantageous role of strengthening by the CFRP was also found in [4]. The authors investigated the web buckling of light steel beams strengthened with CFRP subjected to end-bearing forces. They

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conducted a series of laboratory tests and proposed simple models to predict the improved performance due to CFRP strengthening. They found out that the CFRP strengthening significantly increases the web-buckling capacity especially for those with large web depth-to-thickness ratio. Another highly important issue is the fatigue life of structural steel elements. The aptitude of CFRP in enhancing the load-carrying capacity and in extending the fatigue life of structural steel elements was discussed in [5], [6]. The main conclusions were that CFRPs bonded around the tip zone reduce the fatigue crack growth and extend the fatigue life; on the other hand, high strain concentration in the CFRP tape close to the cracked section causes a potential debonding area and can result in significant increase of the fatigue crack propagation.

Very interesting investigation concerning the modifications of the provisions implemented in EC3 and AISI specification to estimate the ultimate loads of CFRP-strengthened cold-formed steel lipped channel columns was presented in [7]. It was found that formulas originally developed for bare steel members such as ''effective width'' or ''Direct Strength Method'' provide, in several cases of CFRP-strengthened cold-formed members, unsafe estimation. This means that the existing design method must be adequately modified in order to take into consideration the specificities of CFRP-strengthening thin-walled steel members.

In response to the lack of widely used and recognized modern methods of strengthening the thin-walled structures, in this paper, the experimental research of thin-walled sigma beams strengthen with CFRP tapes is performed.

II. Experimental Research

Experimental tests were carried out on a sigma thin-walled beams with a height of 140 mm, the flange width of 70 mm, a wall thickness of 2.5 mm, and other geometrical dimensions which are presented in Fig. 1. The geometrical characteristics of Σ140x70x2.5 based on producer data are shown in Table I. Beams were made of steel S350 GD and manufactured in the company Pruszyński. As a strengthening, the carbon fiber tapes Sika CarboDur S with a thickness of 1.2 mm, a width of 50 mm, and modulus 170 GPa were used. Tapes were adhered to the beams with an adhesive SikaDur®- 30 commonly used for structural reinforcement. The adhesive was prepared according to the manufacturer's instructions, and the strengthened beams were tested after a minimum seven-day period after the bonding of the CFRP tape to achieve full adhesive strength. The applied adhesive thickness was 1.3 mm.

A. Material Tests

In order to determine material strength characteristics, laboratory tests on five samples cut from steel sigma profiles were conducted. The shape and size of samples used in the laboratory tests correspond to the requirements of PN-EN ISO 6892-1: 2009. Measurements of longitudinal and transversal strain of the sample were performed using a biaxial extensometer, as seen in Fig. 2. The material strength characteristics obtained from laboratory tests for five tested samples are presented in Table II.

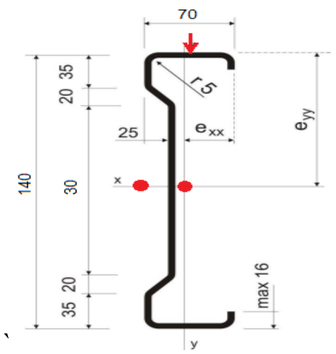


Fig. 1 The geometry of Σ140x70x2.5

TABLE I
THE GEOMETRICAL CHARACTERISTIC OF Σ140X70X2.5 BASED ON PRODUCER DATA

Weight [kN/m]	FA [cm^2]	e_{xx} [cm]	e_{yy} [cm]	Jx [cm^4]	Jy [cm^4]	Ix [cm]	Iy [cm]
6.13	7.81	2.61	6.95	223	38.8	5.34	2.23

TABLE II
THE RESULTS OF MATERIAL STRENGTH CHARACTERISTICS

Number	S_o [mm^2]	R_m [MPa]	E [GPa]	ν [-]
1/1/01/17	52.814	473.913	201.320	0.271
1/2/01/17	52.659	474.428	202.030	0.288
1/3/01/17	52.293	474.804	-	-
1/4/01/17	52.891	472.220	202.040	0.288
1/5/01/17	52.891	472.220	202.040	0.288
arithmetic mean value	52.699	473.560	201.797	0.282
standard deviation	0.243	1.172	0.413	0.010

The initial cross-sectional area S_o is defined as the mean value of the measurement area of the three cross-sections in the middle of the parallel part of the test sample in accordance to PN-EN ISO 6892-1: 2009. Based on the maximum value S_o and maximum external load value, a tensile strength of steel R_m was determined.

During the laboratory tests for samples numbered 1/1/01/17, 1/2/01/17, and 1/4/01/17, biaxial extensometer was used, which allowed to determine the longitudinal and transversal deformation, and thus Young's modulus and Poisson's ratio. It is worth noting that the obtained arithmetic mean value of Young's modulus is equal to 201.8 GPa, which is true because the samples were made of galvanized steel. Commonly Young's modulus of the steel is taken as equal to 205 GPa and of zinc 80 GPa. Assuming that zinc represents approximately 3% of the cross sectional area of the sample, Young's modulus can reach a value in the range of 201 - 202 GP.

B. Full Scale Laboratory Tests

The full scale laboratory tests included six simply supported, single-span beams subjected to a uniformly distributed load. The load was applied to the sample by means of steel cables, according to patent [8], in seven points along the span of the beam, in a way to reflect the uniformly distributed load. Spacing of the beam supports was 220 cm. The overall view of the laboratory stand is illustrated in Fig. 3.

Fig. 2 Laboratory stand and specimens used to determine strength characteristics of steel

Fig. 3 Full scale laboratory stand [9]

Details of laboratory stand concerning the beam support are shown in Fig. 4 (a). It can be seen that the application of the bolt connection allows free rotation in the plane of the beam, while the use of a short rectangular tube with dimensions corresponding exactly to the dimensions of the beam cross-section prevents the rotation out of the plane. Such modeling of boundary conditions in the laboratory stand reflects very accurately the theoretical boundary conditions so-called fork support. In order to apply the load over the whole width of the flange, between each steel cable and the beam, a rectangular wooden separator was placed. In addition, these elements prevent the contact between the beam and the cables. The details of this solution are presented in Fig. 4 (b).

Scheme of laboratory stand with the spacing of the applied beam forces and location of displacement and strain gauges is presented in Fig. 5. The displacement of each beam was measured using the four displacement gauges - three in the horizontal direction and one in the vertical direction, placed in the middle of the span. In the case of the five beams, a measurement of strain was made using six strain electrofusion gauges TENMEX TFs-10, the resistance of 120 Ω ± 0.2%. Experimental studies were carried out in the Laboratory of Civil Engineering Technical University of Lublin in the test machine Zwick & Roel controlling the growth of the load specified by the extending press piston with a speed of 1 mm/min, recording the force at 0.01 s.

(a) (b)

Fig. 4 Details of laboratory stand: (a) detail of the beam support (b) detail of rectangular wooden separator

In order to have the reference results, two first beams numbered B7 and B3 were tested as bare beams, and only beam B3 was tested using electrofusion strain gauges (Fig. 6 (a)). Beams B4 and B5 have been strengthened in tensioned zone by CFRP tape placed in the middle of the width of the upper flange (Fig. 6 (b)). Beams B1 and B8 have been strengthened in compressed zone by CFRP tape placed in the middle of the width of the bottom flange at the inner side (Fig. 6 (c)).

Before the laboratory tests on all tested beams, 5 cm x 5 cm grid was drawn to ensure the grid for the geometric imperfections measurements and the gauges location. Measurements of the local geometrical imperfections covering the flange width, web height and thickness of the cross-section (Bg, Bd, g, H) were made using calipers. The measurements of global geometrical imperfections including in plain (z_i) and out of plain (x_i) deflections along the beam length were carried out with laser, placed at one end of the tested beam and ruler, making continue readout at every 5 cm with an accuracy of 0.5 mm.

The results of measurement of initial geometric imperfections provided for the selected beam are shown in Figs. 7 and 8, related respectively to dimension of cross-sectional walls (local geometrical imperfections) and straightness of the beam. One can notice that deviation of straightness of the beam reaches 2 mm, while the deviation of cross-sectional height reaches up to 3 mm. In the case of thin-walled structures, this can have a significant impact on the structural response and reliability of the received results.

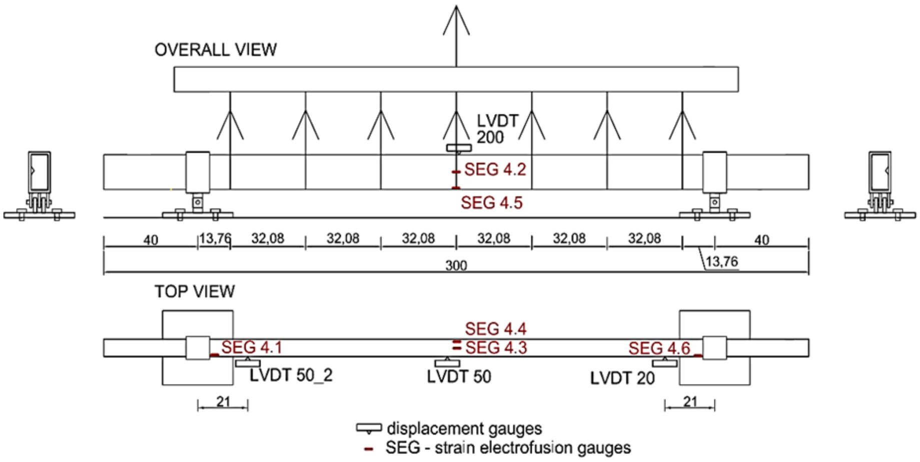


Fig. 5 Scheme of laboratory stand

(a)

(b)

(c)

Fig. 6 CFRP tape location (a) B7 and B3; (b) B1 and B8; (c) B4 and B5

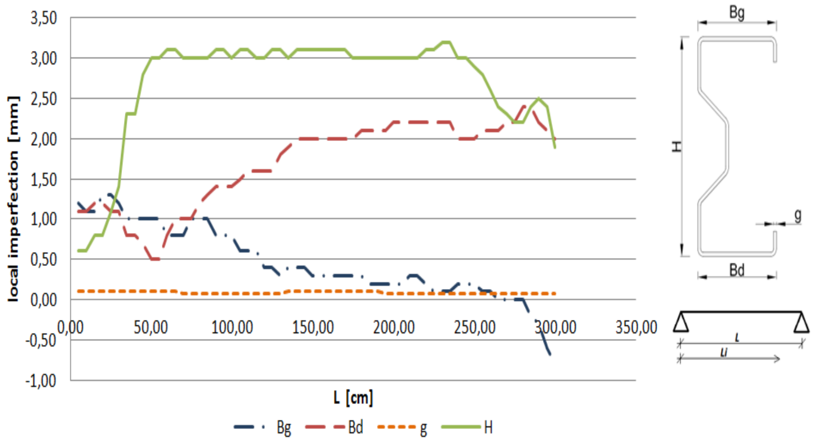


Fig. 7 Local geometrical imperfections including dimension of cross-sectional walls along the beam length

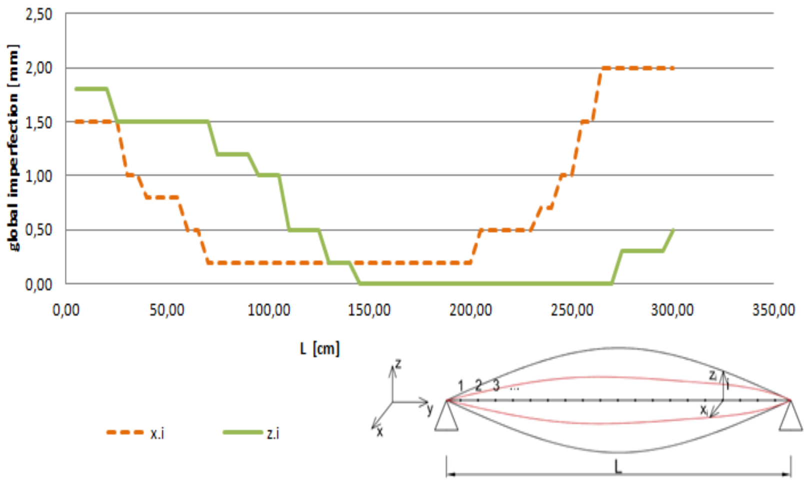


Fig. 8 Global geometrical imperfections including in plain (zi) and out of plain (xi) deflections along the beam length

III. Experimental Results

The experimental tests were carried out in the abovementioned three groups differing in the way of strengthening with CFRP tape. In each group, two series of tests were performed. In order to compare the influence of CFRP strengthening on structural response, the relationships between external load and displacements are summarized in the following figures.

Fig. 9 shows a relationship between external load and displacements of the test machine piston (vertical displacement). At each load level, the best results were obtained when the CFRP tapes strengthening was placed at the tension flange (beam B4 and B5). Slightly poorer results were obtained for the beams B1 and B8 in which the CFRP tape was located in flange at compression part of beam. The most unfavourable results were obtained for the bare beams (B3 and B7). The extreme discrepancy of the obtained results was about 14%.

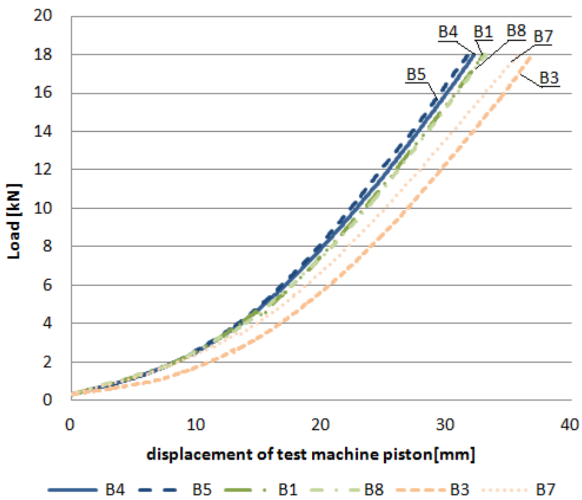
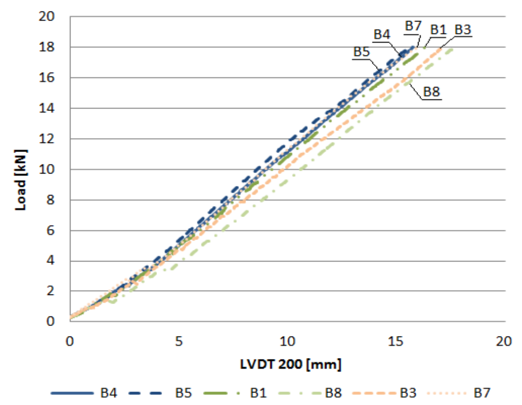
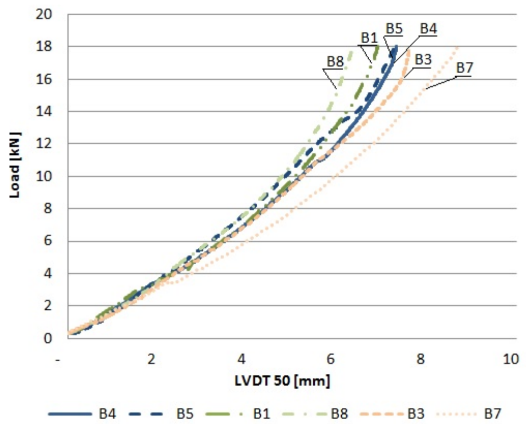


Fig. 9 Relationships between external load and displacements of the test machine piston

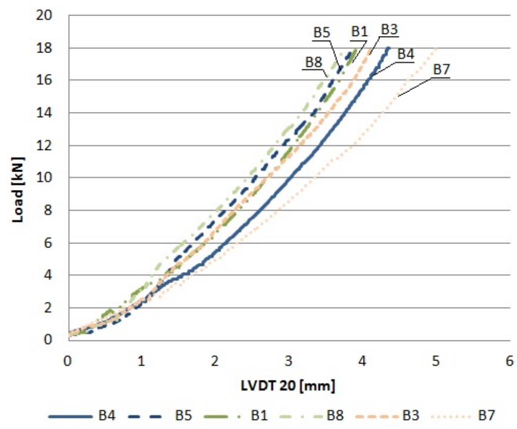


(a)

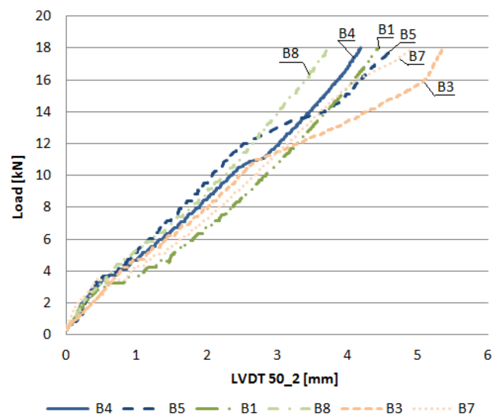


(b)

Fig. 10 Relationships between external load and displacements read by the gauges (a) LVDT 200 (b) LVDT 50



(a)



(b)

Fig. 11 Relationships between external load and displacements a) LVDT 20 b) LVDT 50_2

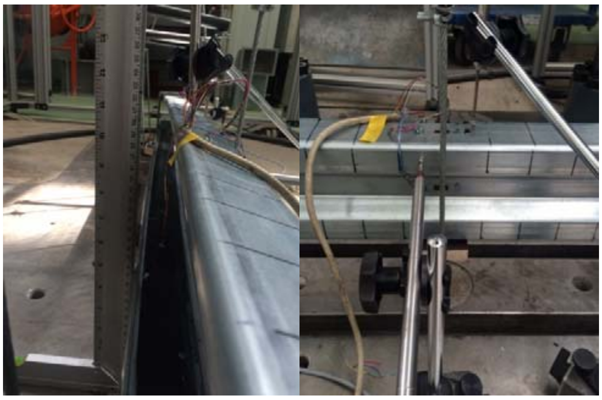
In Fig. 10 (a), relationship between the load and the vertical displacement of the beam in the middle of its span read by LVDT 200 gauge is presented. For each load level, the best results were obtained when CFRP tape strengthening was placed at the tension flange (beam B4 and B5). The most similar results were obtained for the bare beam B7 and strengthen in compression part beam B1. This graph significantly differs from the graph presented in Fig. 9, which can be caused by error readout of the gauge resulting from geometric imperfections and large torsion of the beam flange. Thus, more reliable results seem to be show in Fig. 9.

Fig. 10 (b) shows the relationship between load and horizontal displacement of the beam in the middle of the span read by LVDT 50 gauge. Analyzing the out of the plane deflection readout by LVDT 50 gauge, it could be noticed that the best solution was obtained in case of use the CFRP tape strengthening in compression part of beams cross-section (B1 and B8). Slightly worse results were obtained for beams B4 and B5 and the most unfavorable for the bare beams B3 and B7.

Fig. 11 shows the relationship between the load and the horizontal displacement of the beam in the vicinity of the support readout by LVDT 20 gauge (Fig. 11 (a)) and LVTD 50_2 gauge (Fig. 11 (b)). Comparing the graphs to each other, it can be concluded that most unfavorable results were obtained for bare beams (B3 or B7), and most preferred for the strengthen in compression part beam B8. Other results are interleaved at different load levels, which may result from the initial geometrical imperfections and not perfect contact between the beam and the support.

IV. Critical Remarks Concerning the Laboratory Tests

The presented results were limited to the load of 18 kN. This follows from the fact that the increase in load value was associated with a significant rotational displacement and contact between the beam and the cable. After crossing the load level of 18 kN, slipping of the beam from rectangular wooden separators and inadequate measurement at the displacement gauges was observed. Moreover, due to large rotational displacement also the point of the vertical gauges, its location changed and gotet closer to the flange edge (Fig. 12 (a)). Similarly, the point of the horizontal gauges, initially applied in the middle of the upper web changed its location and slip into diagonal part of web (Fig. 12 (b)).



(a) (b)

Fig. 12 Relationships between external load and displacements a) LVDT 20 b) LVDT 50_2

The abovementioned difficulties associated with performed experimental studies indicate a need to find another method of the beam displacement readout, which would prevent from changing the gauges position. Moreover, it was stated that a certain weakness of conducted laboratory tests was the usage of only linear electrofusion strain gauges attached in a parallel direction to the length of the beam. This enabled the analysis of only the normal stresses and strains. Due to the presence in tested beams of shear stresses resulting from shear and torsion in the next laboratory tests, strain gauges should be placed also in the vertical direction or there should be used the strain gauges in the form of rosettes.

V. Conclusions

In this paper, the experimental research of thin-walled sigma beams strengthen with CFRP tapes is performed. Based on the conducted experimental studies, the following conclusions can be drawn:

- All tested beams were subject to torsion which was caused the way of external load application. Namely, the resultant force of the applied load was located centrally in the flange width and do not match the gravity and shear centre of sigma cross-section,
- Based on the relation load - displacement of the press piston (Fig. 9), best results were obtained in a situation where the CFRP tape was applied to tension flange. It was reported with a load of 18 kN the reduction in vertical displacement of the beam of 13.92% compared to the worst result obtained for bare beam and 5.1% in relation to the strengthen beams in compression part,
- Due to the torsion and horizontal deflection (Fig. 10 (b)) in the middle span of the beam, best results were obtained in a situation where the CFRP tape was applied to compression flange. It was reported with a load of 18 kN the reduction in horizontal displacement of the beam of 25.5% compared to the worst result obtained for bare beam and 11.6% in relation to the strengthen beams in tension part.

In summary, it can be stated that use of CFRP tapes reduces displacements in beam made of sigma profiles subjected to bending and torsion. In the case of torsion, the most adventurous way of strengthening is to attach the CFRP tapes at the compressed zones. What is quite surprising, and differs from the commonly widespread in engineering practice opinion is the best use of CRPF tapes in the tension zones. However, due to insufficient number of laboratory tests and difficulties in laboratory research described above, the obtained result should be regarded as a preliminary and should provide the basis for the preparation of an appropriate laboratory stand, instrumentation, and program of laboratory tests.

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