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Analysis of the Impact of Using CFRP Tapes on the Performance of Bent Thin-Walled Beams Connected with a Sandwich Panel – Pilot Studies

Ilona Szewczak[1]

[1] Faculty of Civil Engineering, Lublin University of Technology, ul. Nadbystrzycka 36, 20-618 Lublin, Poland
E-mail: i.szewczak@pollub.pl

ABSTRACT

The heightening use of thin-walled steel structures necessitates the search for fast and efficient methods of their reinforcement. One solution might be the application of bonded composite tapes. The author of the work has conducted a number of studies so far, which showed a beneficial effect of the use of bonded composite tapes to limit displacements and strains of bent thin-walled sigma beams. In practice, thin-walled steel beams of sigma section are most commonly used as purlins in steel halls, where they cooperate with the sandwich panel. To approach this issue, the present work describes pilot studies in which the effect of the use of composite tapes on the operation of bent thin-walled beams connected with a sandwich panel was analyzed. A four-point bending test was conducted on 9 thin-walled sigma beams Σ200×70×2.3 meters long, connected with a 6 cm thick PIRTECH sandwich panel. Three samples were treated as reference, the next three were reinforced by bonding a composite tape to the lower flange of the steel beam, and the last three were reinforced by bonding a tape to the web. The conducted studies indicate that the adhesion of composite tapes to the lower flange of the thin-walled sigma beam cooperating with the sandwich panel allows for a significant reduction in beam strains and vertical displacements.

Keywords: thin-walled steel beam, sigma profile, sandwich panel, CFRP tape

INTRODUCTION

The increasing use of cold-formed thin-walled steel beams in building structures prompts the search for quick and efficient methods of reinforcing such elements. In the case of thin-walled structures, due to the wall thickness of the section, performing reinforcements by welding is not recommended. One of the solutions may be to perform reinforcements by bonding. Hence the idea of using bonded composite tapes to reinforce thin-walled steel structures. Composite tapes are successfully used to reinforce concrete, masonry, and also steel structures, made of hot-rolled elements [1, 2, 3]. There is also a growing number of publications dedicated to reinforcing thin-walled steel structures. Most of them concern the reinforcement of compressed thin-walled elements of a c-section [4, 5], square [6], or round [7]. The author of this work, together with the team, conducted a number of studies on the reinforcement of bent beams of sigma section, reinforced with CFRP (Carbon Fiber Reinforcement Polymers/Plastics) tapes [8, 9]. While reviewing the literature, works dedicated to the reinforcement of thin-walled steel roof purlins of the type reinforced with pre-stressed CFRP laminates [10] were found. Cold-formed elements (with C, Z, or Σ sections) subjected to bending, due to, among other things, thin walls, the location of the center of gravity of the section or open section, are prone to destruction through various forms of instability (local or global) or plasticity. Both in the case of compressed and bent elements, the application of composite tapes (CFRP) allowed for a meaningful reduction in the values of strains and displacements.

In building practice, sandwich panels are often used as roofing for steel halls. In scientific publications, there are increasingly more studies on thin-walled steel elements cooperating with a sandwich panel. The issue of connection stiffness of thin-walled Z-type beam with a sandwich panel [11], rotational resistant stiffness of the zed-purlins connection with sandwich panels [12] is examined and described. However, no publications dedicated to the reinforcement of thin-walled steel elements connected with a sandwich panel were found. Therefore, this work presents preliminary laboratory tests concerning the analysis of the consequence of the usage of CFRP tapes on limiting displacements and deformations of thin-walled sigma type steel beams connected with a sandwich panel.

RESEARCH STAND AND PREPARATION OF SAMPLES

Nine samples were tested to a four-point bending test. The points of load application were chosen in such a way that the bending moment value obtained in the middle of the sample's span corresponded to evenly distributed load. The load from the press on the samples was transferred through hot-rolled double T-beams with a base width of 12 cm and a length corresponding to the width of the layered plate (80 cm).

Each of the samples consisted of a thin-walled sigma type steel beam with a height of 200 mm, base width of 70 mm and wall thickness of 2 mm, made of S350GD steel. The length of the beams was 300 cm. To the beams were screwed PIRTECH roof layered plates from Pruszyński Sp. z o.o., with a polyurethane foam core, thickness of 6 cm, length of 300 cm and width of 80 cm. The applied width was dictated by the limitations of the laboratory stand. The beams were connected to the sandwich panel with self-drilling, self-tapping connectors with EPDM washers, measuring 5.5x75 mm. The first connector was placed 10 cm from the beginning of the panel and the subsequent ones were spaced every 31 cm.

Subsequently, 6 samples were reinforced by adhering CFRP Sika CarboDur S 512 tape with cross-sectional dimensions of 50x1.2 mm. The total length of the carbon fiber tape used was 201 cm. This allowed for an anchorage length of 30 cm. In the paper [13], the authors defined the effective anchoring length of composite tapes as the minimum length that allows the transfer of the maximum load by composite tapes. Such anchoring length of tapes was determined as the most effective in the case of reinforcing sigma thin-walled beams, which is described in the paper [14]. In the article [14] also describes how to determine the effective anchorage length. The CFRP tapes were bonded to the degreased and matted topmost layer of the thin-walled beams using SikaDur-30 adhesive. It is a two-component, thixotropic epoxy resin-based adhesive with good adhesion to most construction materials. It is characterized by high mechanical strength and is intended for joining and structural reinforcement using steel plates or composite tapes. The thickness of the applied adhesive layer was 0.65 mm and was adopted based on the tests described in the paper [15]. In order to obtain the desired thickness of the adhesive layer, steel sheet templates had been prepared of, in which a cutout was made with a width equal to the width of the CFRP tape and a height equal to the thickness of the tape increased by 0.65 mm.

In the first stage, a slightly thicker layer of glue was applied to the tape. Then, using the template, the excess of glue was removed, but the glue surplus necessary to properly press the tape to the beam surface was left. The tape was applied to the beam, and template was pressed towards and moved over it. As a result of this process, excess glue was removed and collected from the edges of the tape.

The basic strength parameters of the steel and CFRP tape used in the study are compiled in Table 1. Strength parameters of the SikaDur-30 adhesive were taken from the manufacturer's catalog cards and quoted in [14] and [15] and in Table 1.

Three samples were left without reinforcement, treating them as reference samples (B1R, B2R, B3R). The next three samples were reinforced with composite tape placed on the outer side of the lower flange of the beam (B1D, B2D, B3D), and the last three were reinforced by adhering composite tape on the inner side of the web (named during laboratory tests as B1S, B2S and B3S). The sample nomenclature and the way of placing CFRP tapes and strain gauges used for strain measurement (T1, T1), are shown in Figure 1.

Before connecting the beams with the sandwich panel, a check was made for initial geometrical imperfections of the thin-walled beams. This is due to the fact that thin-walled beams are very susceptible to local and global forms of loss

Table 1. Basic strength parameters of steel, CFRP tape and adhesive

Thin-walled steel beams	
Poisson's ratio	n = 0.307
Young's modulus	E = 207.87 GPa
Sika CarboDur S512	
Poisson's ratio	v = 0.308
Young's modulus	E = 165 GPa
SikaDur-30 adhesive	
Minimum compressive strength after 7 days	75 MPa
Compressive modulus	9600 MPa
Minimum tensile strength after 7 days	26 MPa
Minimum shear strength	16 MPa
Minimum peel strength after 7 days	21 MPa
Shrinkage	0.04%

of stability and any initial geometrical imperfections can significantly contribute to the deepening of such phenomena. The ATOS COMACT SCAN system, which allows for precise measurement of even long elements and then thanks to the GOM software it is possible to overlay the obtained contour of the tested object on the template image, made for example in AutoCad, was used in the study of imperfections. Prior to commencing the measurements, all beam surfaces were painted with chalk spray to matte the surfaces. The 3D scanner measurements were conducted by a person with the appropriate training. The software enables distance measurements between individual indicated points or surfaces. This way, measurements of beam height and flange widths were carried out. The beam's height ranged from 199.431 mm to 199.837 mm. The spread between the extreme measurements does not exceed 0.5 mm, indicating the high-quality manufacture of the beams. The nominal section height is 200 mm. The measured height is within the dimensional tolerance limits, which for this cross-section is 1 mm. For flange width measurements, the measured values ranged from 69.54 mm to 69.936 mm. The dimensional tolerance for the nominal flange width of 70 mm is 0.5 mm. The section dimensions were within the allowed dimensional tolerances. Simultaneously, all beams showed a deflection reaching 3 mm in the beam length, as seen in Figure 2. All beams had very similar initial deflection, therefore, in conducting studies related to reference beams, this should not have a major significance in formulating final conclusions.

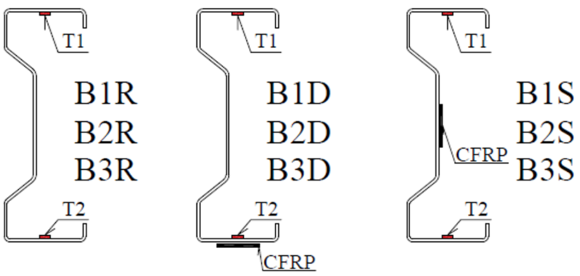

Fig. 1. Sample names, location of CFRP tapes and strain gauges T1 and T2

Before proceeding with the laboratory tests, measurement points were glued onto all samples, where displacements were read during the test using the Aramis system.

LABORATORY TESTS

The testing of the samples was carried out in a four-point bending scheme in a Zwick&Roel press. The specified load increment was 1 mm/

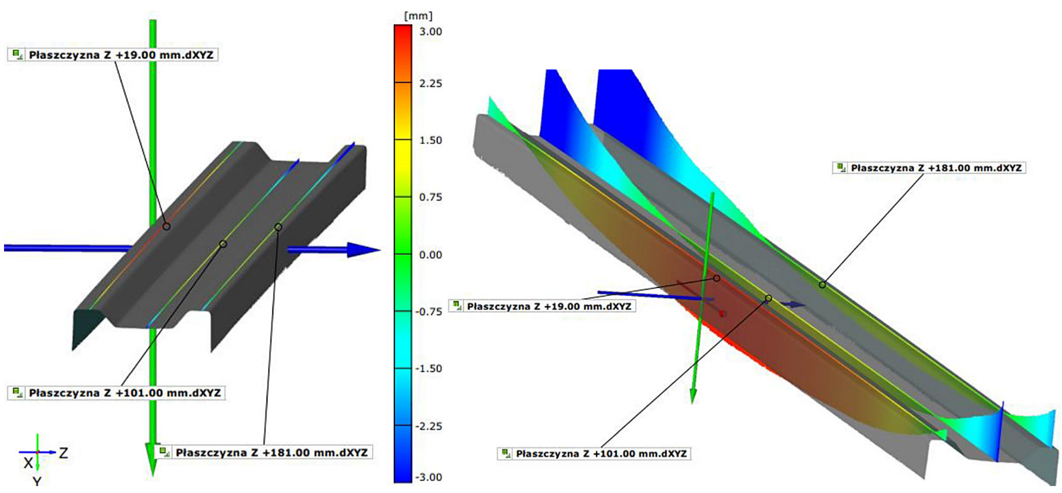

Fig. 2. Beam deflection along profile and deflections in relation to CAD model

min of press piston movement and the results were read every 0.01 s. The scheme of the test stand is shown in Figure 3a, and an example photo of a laboratory stand is shown in Figure 3b.

During the test, strain measurements were made using two TENMEX TFs-10 120Ω ± 0.2% strain gauges, located in the midway of the span of the tested sample on the lower and upper flanges of the cross-section (the location of strain gauges T1 and T2 is shown in Figure 1), and displacement measurements were made at nominated points in the middle of the cross-section span using the Aramis system. The use of the Aramis system allowed for measurement of displacements in the vertical and horizontal directions at selected points. This was particularly important as in the case of sigma section beams tested without sandwich panels during bending, the beam underwent significant torsion, which did not allow for deflection testing with traditional sensors. In the described tests, a LVDT sensor was also used as a control, which measured displacement in the vertical direction in the middle of the beam span and in the middle of the flange width.

RESULTS

During the test, the increase in load was continued until the samples were destroyed. The destructive force was considered to be the load value at which the CFRP tapes were detached or the sandwich panel was completely destroyed (core fracture or significant delamination of the panel). During the tests, sample destruction was observed by detaching CFRP tapes at the adhesive - steel interface, with all the adhesive remaining on the CFRP tapes. After removing the samples from the press and unscrewing the sandwich panels, permanent deformations in thin-walled steel beams were also visible. Photographs of typical forms of destruction are shown in Figure 4.

To enable a comparison of the obtained results, it was settled to restrict the analyses to the smallest load value at which the sample was destroyed. Finally, the destructive force was considered to be a load of 20 kN. This was the load value at which complete destruction of the layered plate occurred in sample B3S. Figure 5 presents the results of strain measurements at the location of

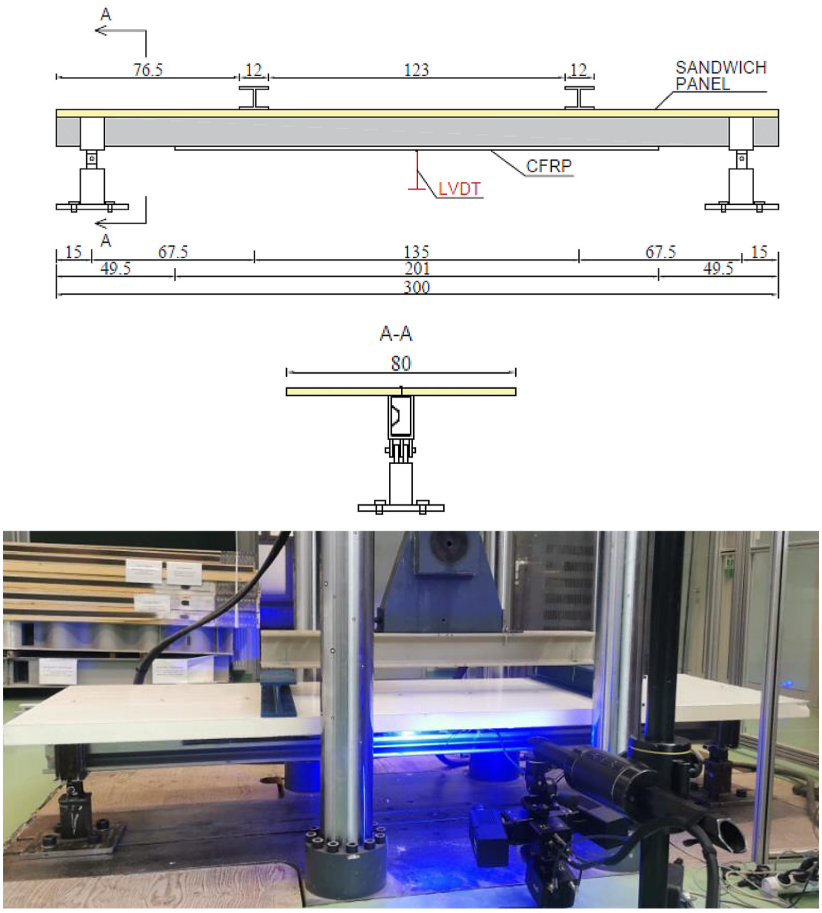

Fig. 3. a) Scheme of the test stand, b) photo of the stand

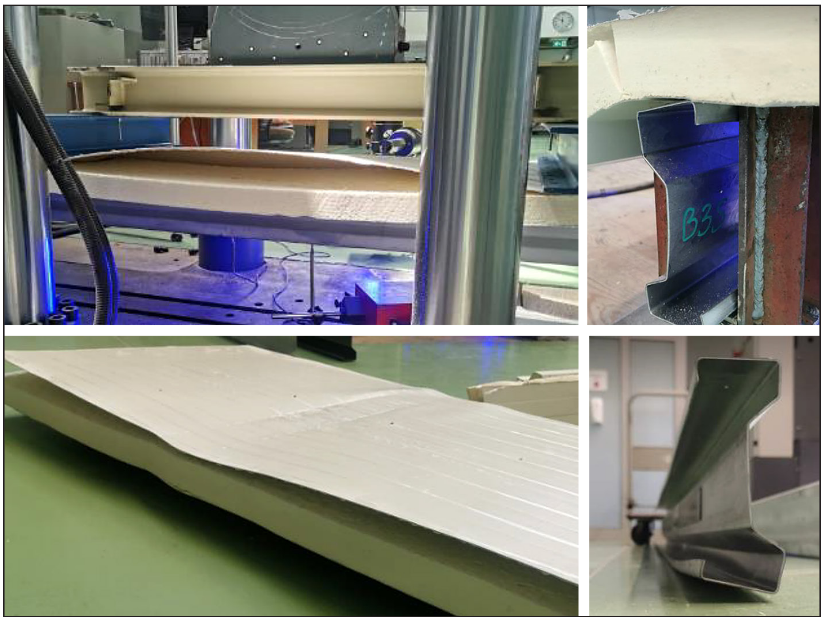

Fig. 4. Typical forms of beam destruction

strain gauge T1 (compressed flange) and Figure 6 presents the results of strain measurements at the location of strain gauge T2 (tensioned flange).

To enable analysis of the results, Table 2 was developed, in which the strain values of analysed samples at a load of 20 kN are presented.

The average value of the recorded strains was calculated for individual groups of samples. The attained results desired that the application of composite tape reinforcement on the lower flange reduces the strain values in both the compressed and tensioned shelf compared to the

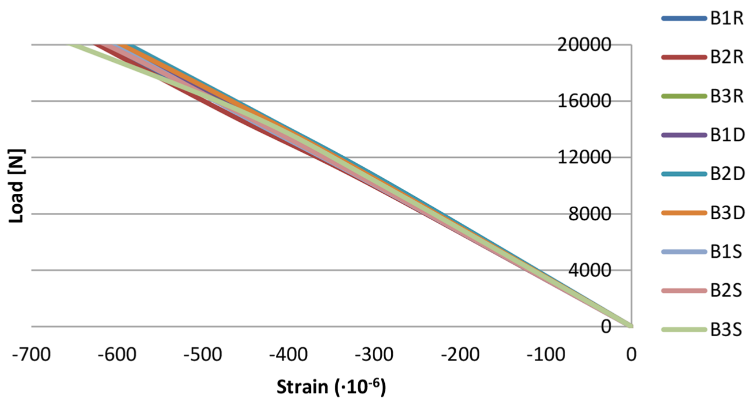

Fig. 5. The graph showing the load-strain relationship at the location of the T1 electro-resistance strain gauge

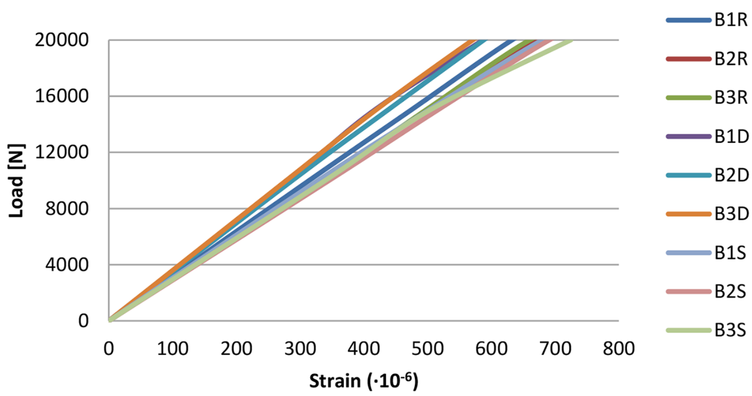

Fig. 6. The graph showing the load-strain relationship at the location of the T2 electro-resistance strain gauge

Table 2. Strain values in each of the analyzed samples at a load of 20 kN

Parameter		B1R	B2R	B3R	B1D	B2D	B3D	B1S	B2S	B3S
Strain (·10^{-6})	T1	-617	-622	-606	-612	-587	-595	-608	-613	-651
			-615			-598			-624	
	T2	632	672	660	587	588	571	680	691	725
			655			582			699	

reference samples. Placing composite tapes in the web of the thin-walled beam does not reduce the strain values (taking into account the average value), and if we omit sample B3S we can observe only a slight reduction in the strain values in the compressed flange compared to the reference samples.

The sample displacement was measured using the Aramis system. At the same time, for several samples, vertical displacements were measured using the LVDT sensor. Figure 7 shows the results of displacements read using the LVDT sensor. Table 3 shows the values of vertical and horizontal displacements read using the Aramis system at the point in the midway of the span of the tested sample on the lower flange, at a load value of 20 kN. An exemplary readout of displacements at points in the midway of the span of sample B1R, obtained from the GOM Correlate program, is shown in Figure 8.

Applying reinforcement to the samples with composite tape placed on the lower flange contributed to a slight limitation of deflection in both the vertical and horizontal direction compared to samples without reinforcement. The application of reinforcement on the web did not result in limitation of sample displacement compared to reference samples.

The tests carried out showed that the sigma thin-walled beam connected to the layered plate undergoes bending and twisting during loading. Blocking the upper flange by connecting it to the sandwich panel resulted in more than a doubling of horizontal displacements of the lower flange compared to tests of the beams alone in a four-point bending scheme, described in [8, 9].

CONCLUSIONS

The pilot tests described in this paper aimed to demonstrate the impact of using CFRP tape reinforcements on limiting displacements and strains of sigma thin-walled steel beams cooperating with a sandwich panel. Based on the tests carried out, it was found that:

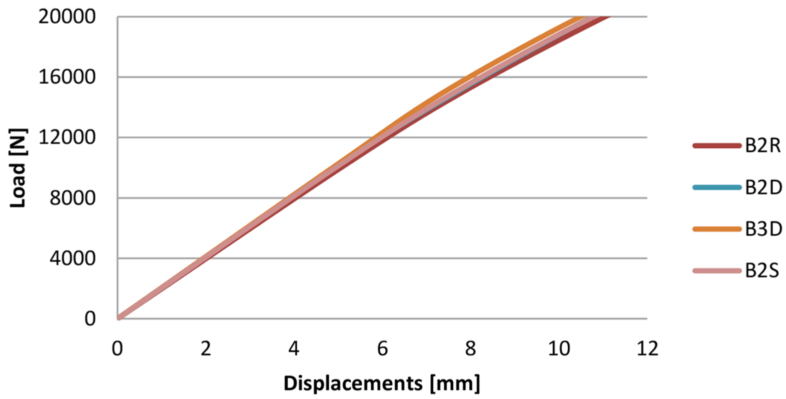

Fig. 7. The graph showing the load-displacement relationship at the point of application of the LVDT sensor

Table 3. Displacement values of individual samples at a load of 20 kN

Displacement	B1R	B2R	B3R	B1D	B2D	B3D	B1S	B2S	B3S
Horizontal displacement [mm]	-6.31	-6.02	-4.44	-6.13	-4.78	-5.32	-	-5.87	-6.13
		-5.59			-5.41			-6.00	
Vertical displacement [mm]	12.61	13.84	13.33	12.34	13.48	13.78	-	13.39	13.52
		13.26			13.20			13.46	

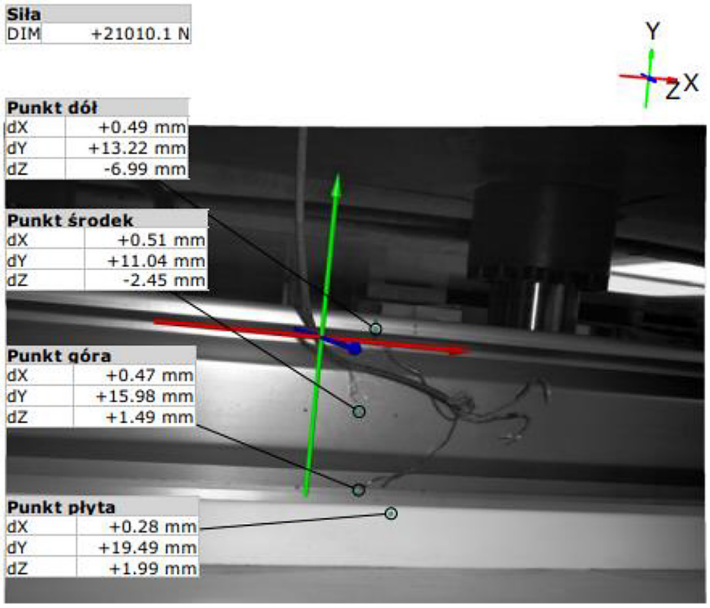

Fig. 8. Presentation of the results of displacement measurements using the Gom Correlate program

The use of carbon fiber composite tape on the stretched lower flange of the beam allows for reduction of strains in the upper flange (at the location of strain gauge T1) on average by 2.7%, and in the lower flange (at the location of strain gauge T2) on average by 11.1%, compared to reference samples.

The use of CFRP tape on the web does not result in limitation of strains at the location of strain gauges T1 and T2, compared to reference samples. The usage of carbon fiber composite tape on the lower flange of the test sample allows for limitation of horizontal displacements of the lower flange in the midway of the beam span by an average of 3.2%, and vertical displacements in the same point by an average of 0.5%, compared to reference samples. The use of CFRP tape on the web does not result in limitation of vertical and horizontal displacements compared to reference samples.

In order to limit the strains or displacements of sigma section thin-walled beams cooperating with a sandwich panel, it is necessary to apply reinforcement on the lower flange of the steel beam. The application of reinforcement on the web in the tested samples did not result in reduction of displacement and strain values compared to reference samples. This is surprising, as in the case of testing the beams alone in a four-point bending scheme, the application of reinforcements on the web resulted in a reduction of strains in the compressed shelf by an average of 6%, in the stretched shelf by 2%, and a limitation of vertical displacements by 5.5%.

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