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Research Paper

Issues of Thin-Walled Sigma Beams Strengthened by CFRP Tape in the Context of Experimental and Numerical Studies

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In this paper, the results of laboratory tests and numerical analyses of thin-walled beams strengthened with carbon fiber reinforced polymer (CFRP) are presented. In particular, tensile tests of the steel and carbon fiber Sika® CarboDur® S tapes were conducted. Full scale laboratory tests included six sigma beams, each 140 mm high, 3 m long and with a wall thickness of 2.5 mm. The laboratory specimens were assumed as simply supported, single-span beams subjected to a uniformly distributed load. Four of the tested beams were reinforced with carbon fiber tapes, and the other two were not reinforced and were considered as reference beams. Numerical models of the considered beams were developed in the Abaqus program and subjected to validation and verification based on laboratory results. In the paper, special attention is paid to the evaluation of the possibility of increasing the critical load capacity while simultaneously limiting displacements of the beams by appropriate positioning of CFRP tape. The work completes with comparative analysis and conclusions.

Key words: thin-walled beam; strengthened; CFRP tapes.

1. Introduction

The rapid development of civilization in the 21st century brought not only new technologies and facilities in almost every field of life, but also introduced numerous hazards. In the case of civil engineering, this development has caused numerous threats to old built structures. Initially, ideas for strengthening these structures were limited to increasing the cross-section of individual steelwork elements. However, this approach did not always meet the public acceptance due to the visual reception of the modified structure. In addition, the use of such strengthening technique was time-consuming and required significant financial inputs. On the other hand, application of CFRP tapes does not cause such difficulties. CFRP tapes are characterized by excellent mechanical properties of carbon fibers in comparison to other materials. The main mechanical properties of CFRP composites depend on the type and the orientation of carbon fibers, the type of epoxy resin and its percentage content in the final material. The main advantages of CFRP composite materials are: over 10 times higher tape tensile strength in fiber direction compared with conventional structural steel grades, considerable fatigue resistance, and durability due to high corrosion resistance. Moreover, strengthening with CFRP tape is feasible for structures made of various materials such as concrete, steel and wood. Furthermore, application of an adhesive bond between CFRP tape and construction allows for easy and fast application, low labor cost and easy transportation. By contrast, the CFRP disadvantages are low strength in compression-approximately 10% of the tensile strength and even less for interlaminar shear strength, known as debonding. Furthermore, due to the brittleness and susceptibility to stress concentration, CFRP tape cannot be cut, drilled or bended. Another disadvantage of this composite material is the lack of resistance to high temperature due to the presence of epoxy resins. The maximum operating temperature of structures strengthened with CFRP tapes must not exceed 50°C, which requires additional fire protection in CFRP tape-strengthened places.

In 1967, the first attempts to reinforce the structure by bonding steel elements with epoxy resins were made. This idea was initially received with skepticism by the scientific community, especially since long-term studies revealed the appearance of corrosion in resin cracks at the resin-steel interface due to stress and harmful external factors. In 1982, at the EMPA in Switzerland the idea of replacing steel plates with CFRP tapes was presented. In 1985, at the ETH seminar in Zurich, it was declared that the use of 4.5 kg of CFRP tape to reinforce the structure gives the same result as the application of 94 kg of steel. In 1991, the first bridge (one near Lucerne) and the first building (Gossau Town Hall near St. Gallen) were reinforced using CFRP. Initially, CFRP was used to reinforce concrete, stone and wooden structures such as the historic wooden bridge in Sins, Switzerland in 1992. In Poland, only stone and reinforced concrete constructions were initially strengthened by CFRP, among them a bridge across the Vistula River in Chełmno. Nowadays, the application of CFRP tapes to steel bridge girders is widely discussed in literature, e.g., in [8, 9]. In addition, the use of carbon fiber tapes for reinforcing antenna masts was tested with very good results at NC State University and presented in [3]. However, there is not enough research to date on thin-walled cold-rolled steel members, which due to their large capacity ratio with respect to their small weight, have recently found a widespread application in civil engineering practice. It is worth to note that they are used not only as secondary elements but also as main bearing member in a system of steel halls. In view of the fact that in the case of thin-walled profiles it is impossible to perform welded joints and there is a limited possibility to apply mechanical fasteners, the use of CFRP strengthening becomes more and more prevalent in such profiles. Research on reinforced steel thin-walled elements in bending or in compression is also being increasingly reported. The vast majority of publications concern I-section [4, 13, 14], C or Z cross-sections. Even published studies on non-reinforced sigma cross-section beams are rare [7]. The lack of scientific research on the impact of CFRP tapes on stability of steel thin-walled sections has led the authors to study this research topic. A special attention is paid to the use of CFRP tapes to improve the buckling and post-buckling behavior of steel thin-walled profiles.

The effectiveness of applying the FRP materials to provide improvements in the flange and web local buckling and flexural torsional buckling of steel members was investigated in [5]. In that paper, the experimental research demonstrating the feasibility of using small quantities of FRP to provide cross-sectional stability through the bonding of FRP tapes to flange elements was presented. It was assumed that this application did not aim at increasing the load-carrying capacity of the steel section but rather at increasing the critical load of the member. The advantageous role of CFRP strengthening was also presented in [17]. The authors investigated there the web buckling of light steel beams strengthened with CFRP and subjected to end-bearing forces. They 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 members with large web depth-to-thickness ratio. Another highly important issue is fatigue life of structural steel elements. The ability of CFRP to enhance the load-carrying capacity and extend the fatigue life of structural steel elements was discussed in [1, 6]. The main conclusions were that CFRPs bonded around the tip zone reduce the fatigue crack growth and extend the fatigue life, whereas high strain concentration in the CFRP tape close to the cracked section causes a potential debonding area and can result in a significant increase of the fatigue crack propagation. A 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 were presented in [2]. It was found there that the formulas originally developed for bare steel members such as "effective width" or "direct strength method" provide unsafe estimation in several cases of CFRP-strengthened cold-formed members. This means that the existing design methods must be adequately modified to take into consideration the specifics of CFRP-strengthening thin-walled steel members.

2. Laboratory tests

Laboratory tests were carried out on six "Blachy Pruszyński" sigma thin-walled beams with a height of 140 mm, the flange width of 70 mm and a wall thickness of 2.5 mm. Beams were made of steel S350 GD, Young's modulus was $E = 201.8$ GPa, Poisson's ratio $\nu = 0.282$, and Yield's stresses 418.5 MPa. Two beams (B3 and B7) were tested as bare beams and four beams were strengthen by the Sika® CarboDur® S carbon fiber tapes (B4, B5, B1 and B8) of the thickness of 1.2 mm, the width of 50 mm and $E = 170$ GPa. The experimental stand and the preliminary laboratory test including only the results of displacement were described in [12] where preliminary laboratory tests concerning the analysis of the effectiveness of the strengthening steel beams made of thin-walled sigma profiles with CFRP tapes, taking into account both displacement and strain, are presented in this paper. The layout of CFRP tapes on the examined thin-walled beams is shown in Fig. 1.

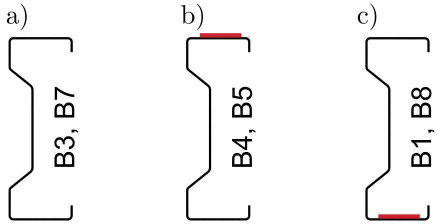

Fig. 1. Layout of CFRP tapes on the examined thin-walled beams: a) bare beams, b) CFRP tape bonded to the tensioned flange, c) CFRP tape bonded to the compressed flange.

Beams B4 and B5 were reinforced with the CFRP tape bonded to the outside surface of the tensioned flange, while beams B1 and B8 were reinforced with CRFP bonded onto the inside surface of the compressed flange. All beams had a span of 2.20 m and were tested on a laboratory stand prepared in accordance with the patent presented in [10]. The load was applied to the sample by means of steel cables at seven points along the span of the beam, in a way to reflect the uniformly distributed load. The model of the laboratory stand is presented in Fig. 2.

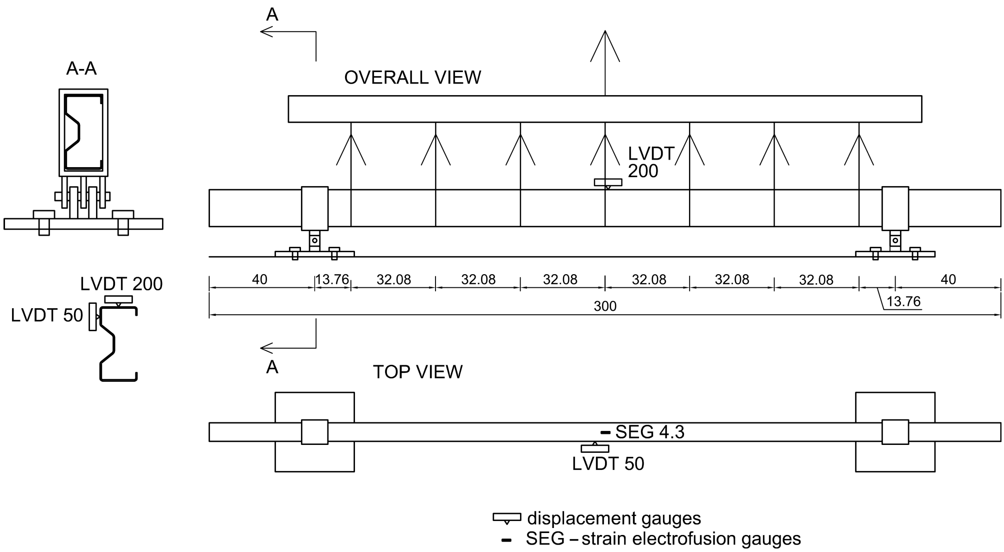

Fig. 2. Scheme of laboratory stand and layout of measuring points for displacement inductive gauges (LVDT) and strain electrofusion gauges (SEG).

During the laboratory tests, the beams were subjected to a torsion, which was caused by the external load application. The load was applied at the bottom flange of the beam, while the sigma cross-section, being a monosymmetrical section, had an offset between the center of gravity, the center of torsion, and finally the point of application of the load, which resulted in an unexpectedly large torsion. Unfortunately, as a result, at the load level of the press piston-about 15–19 kN, the beam began to lean on steel cables that transmitted the load from the press. In order to ensure the reliability of the obtained results, the authors considered only the results of tests for to the load of 16 kN, as only these laboratory results were not distorted and could be compared with the results obtained from the numerical model. In addition, displacement was tested using four standard displacement inductive gauges (two horizontal and one vertical at the middle span of the beam and one horizontal at the supports), which also proved to be incorrect, as the inductive sensor did not read displacement at the same point during the large torsion of the beam.

3. Numerical model

Numerical analyses were performed for sigma beams identical to those tested in the laboratory [12, 15], using the finite element method and ABAQUS® software. Computer simulations were performed using the Newton-Raphson iterative method [12]. The Newton-Raphson method is a useful tool for performing non-linear MES analysis, which is considered to be one of the fastest convergences, especially in the case of contact interaction and large deformations [11]. Material characteristics of steel were described based on laboratory studies. On the basis of the $\sigma-\varepsilon$ relationship obtained in laboratory, the bilinear $\sigma-\varepsilon$ graph was defined in the numerical model, where both elastic characteristics – such as Young's modulus and Poisson's ratio and plastic characteristics such as yield strength and elongation were taken into account. The CFRP tapes were described as an orthotropic material with typical composite material characteristics such as Young's modulus in the longitudinal and transverse direction, Poisson's ratio and Kirchhoff's modulus.

The proposed MES model was developed by taking into account contact constrains in both tangential and normal directions between the beam and non-deformable supports. Boundary conditions fully represented the real test conditions, where the load was applied by the means of seven uniformly spaced cables. Supports were placed at the distance determined at the experimental stage at both ends of the beam. The connection of the CFRP tapes with the corresponding plane (the lower and upper flange of the beam) was made using a TIE-type connection, which resulted in "bonding" the elements described above. The model used the C3D20R solid discretization with three translational degrees of freedom in each of 20 nodes per finite element. In addition, the technique of reduced integration was used in the finite element description. The reduced integration technique enables the removal of false forms of the finite element deformation by using higher order polynomials in the description of the shape function [18]. Supports were modeled using R3D4 non-deformable shell elements with three translational degrees of freedom in each of the four nodes. The composite tape was modeled as a S8R shell element that contained six degrees of freedom in each of the eight nodes per finite element and by the technique of reduced integration. To obtain correct results in the case of bending within the

Fig. 3. Numerical model with the mesh representation.

numerical analysis, the mesh pattern of the solid element was applied in such a way that at least three finite elements were included on the wall thickness, thus forming a neutral layer.

The size of the numerical problem expressed by the number of 45 000 finite elements and 61 400 nodes in the general numerical representation indicates the significant complexity of the numerical model.

4. Comparative analysis of laboratory and numerical research

Comparative analysis of laboratory and numerical tests concerns the strain, vertical and horizontal displacement measured by strain electrofusion gauges and displacement inductive gauges located as shown in Fig. 2.

4.1. Strain analysis

Figure 4 shows the force – strain relationship measured at the midspan of the beam on the tensioned flange (strain electrofusion gauge 4_3, see Fig. 2). The strain values read from SEG 4_3 for the beams reinforced with the CFRP tape bonded to the tensioned flange (B4 and B5) and the numerical model (Abaqus B4) for the analogous reinforcement method are shown in Fig. 4a, whereas Fig. 4b presents the strain values read from SEG 4_3 for beams reinforced with the CFRP tape at the compressed flange (B1 and B8) and the analogous numerical model (Abaqus B1). Finally, Fig. 4c shows the strain results obtained for the bare beams, without reinforcement (B3 and Abaqus).

To analyze the effect of CFRP reinforcement, the percentage parameter describing the strain reduction in the thin-walled beam was determined according to the following formula:

$$m_i = \frac{s_{\mathrm{ref}} - s_i}{s_{\mathrm{ref}}} \cdot 100\%, \tag{4.1}$$

where m – percentage parameter describing the reduction of strain due to i-th CFRP reinforcement method, s_{ref} – strain for the bare beam (reference strain), s_i – strain for the reinforced beam by i-th CFRP reinforcement method, $i = 1$ – reinforcing with the CFRP tape at the tensioned flange and $i = 2$ – reinforcing with the CFRP tape at the compressed flange.

Based on the strain analysis, it was found that the use of the CFRP tape at the tensioned flange allowed the actual strain to be reduced by $m_1 = 13.6\%$ for the laboratory tests (B4 and B5). In addition, at the same point, the strain values obtained from the numerical model (Abaqus B4) show a $m_1 = 17.4\%$ strain reduction. On the other hand, application of carbon fiber tapes at the compressed flange produces the strain reduction by $m_2 = 6.8\%$ for the laboratory tests (beam B1 and B8) and by $m_2 = 2\%$ for the numerical model by

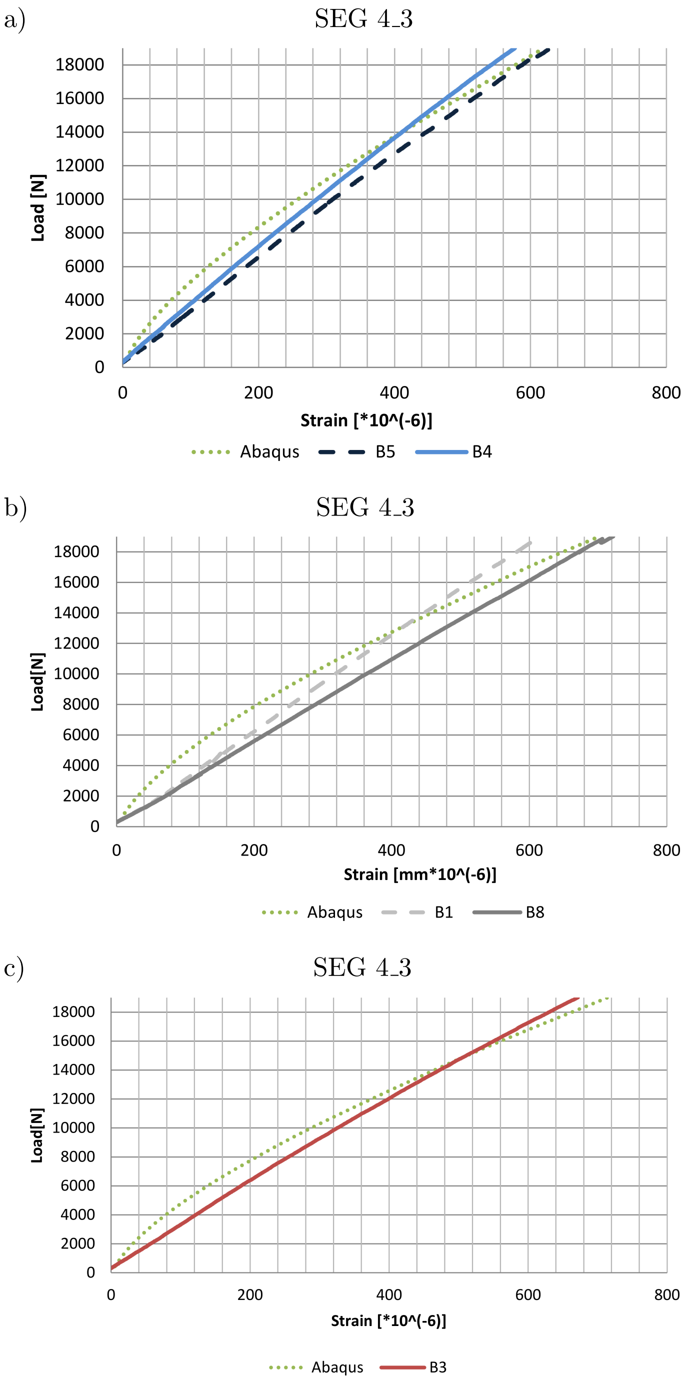

Fig. 4. The force – strain relation obtained from the numerical model and SEG 4_3 readout for the beams: a) reinforced at the tensioned flange, b) reinforced at the compressed flange, c) bare beams.

(Abaqus B1). Please note that the calculations of the strain reduction parameter m were carried out for strain readings obtained from the SEG 4_3 at a load level of 16 kN. It is worth to mention that the results obtained in laboratory tests and numerical analysis of sigma beams remain in good agreement and reflect certain trends observed in the impact of CFRP tapes on the work of beams. This fact confirms the same character of deformation in the numerical model and laboratory test, as shown in the displacement map in Fig. 5.

a) b)

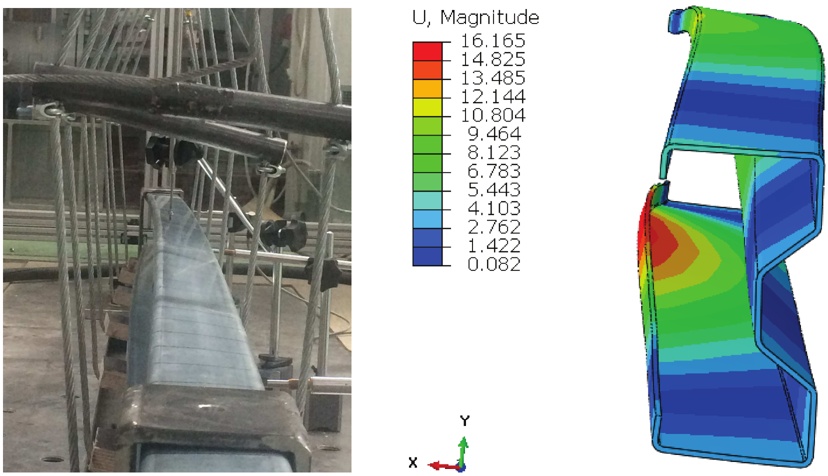

FIG. 5. Comparison of beam deformation pattern: a) laboratory test, b) numerical model (displacement map).

4.2. Displacement analysis

Comparative analysis of laboratory and numerical tests concerns beam displacements at point of occurrence of displacement inductive gauges LVDT 200 and LVDT 50 (Fig. 6).

To analyze the effect of CFRP reinforcement in terms of displacement, the percentage parameter describing the displacement reduction in the thin-walled beam was determined according to the following formula:

$$\rho_i = \left(1 - \frac{u_{\mathrm{ref}} - u_i}{u_{\mathrm{ref}}}\right) \cdot 100\%, \tag{4.2}$$

where ρ_i – percentage parameter describing the reduction of displacement due to i-th CFRP reinforcement method, u_{ref} – displacement for the bare beam (reference displacement), u_i – displacement for the reinforced beam by i-th CFRP reinforcement method.

Please note that the calculations of displacement reduction parameter ρ_i were carried out at a load level of 16 kN.

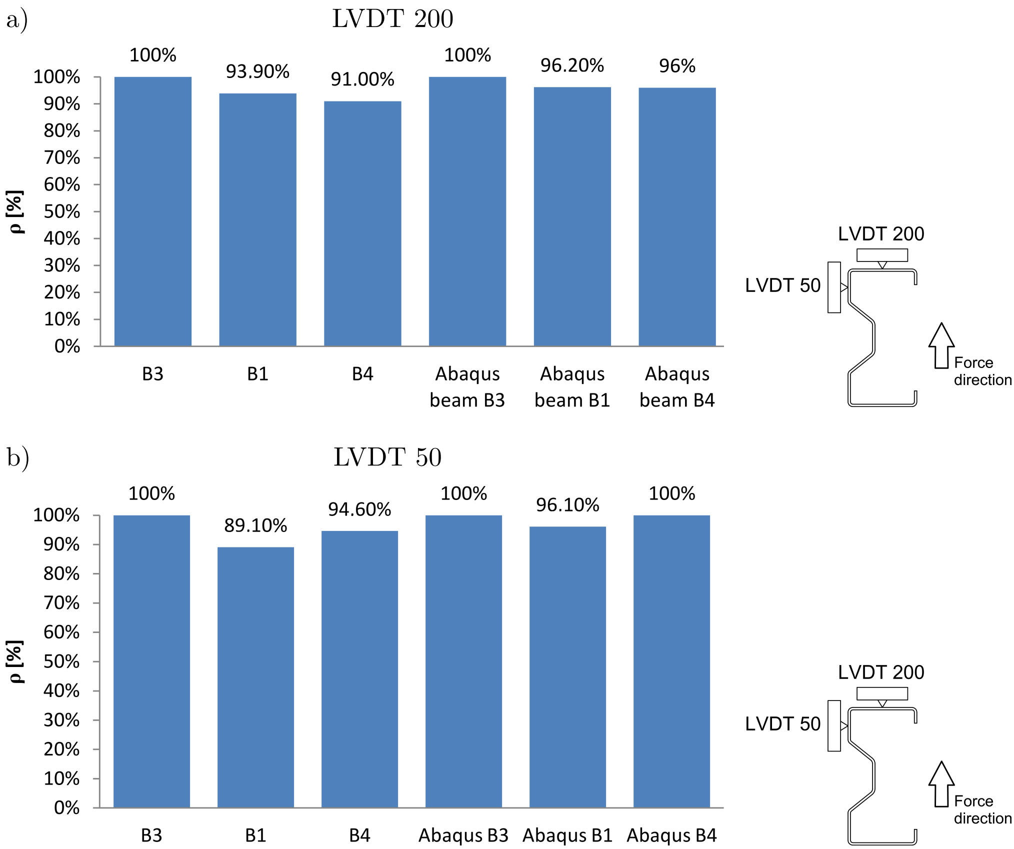

FIG. 6. Displacement reduction parameter ρ_i: a) vertical displacement LVDT 200, b) horizontal displacement LVDT 50.

Figure 6 shows the percentage parameter ρ_i describing the reduction of displacement at the midspan of the beam. The vertical displacement reduction parameter ρ_i based on the readout of LVDT200 displacement inductive gauges for the beams reinforced with the CFRP tape bonded to the tensioned flange (B4), at compressed flange (B1) and the numerical model for the analogous reinforcement method (Abaqus B4, Abaqus B1), is presented in Fig. 6a. In turn, Fig. 6b shows the horizontal displacement reduction parameter ρ_i based on the readout of LVDT 50 displacement inductive gauges for the analogous CFRP reinforcement method as in the case of LVDT200. The bare beams, without reinforcement (B3 and Abaqus B3) are regarded as reference elements.

One can notice that the best results in the case of vertical displacement are obtained using the CFRP tape at the tensioned flange, which enables the actual vertical displacement to be reduced by $\rho_1 = 9\%$ for the laboratory tests (B4, LVDT 200) and by $\rho_1 = 4\%$ for the numerical model (Abaqus B4). However, in the case of horizontal displacement, the best results are obtained when the CFRP tape is applied at the compressed flange, which produces the strain reduction of $\rho_2 = 10.9\%$ for the laboratory tests (B1, LVDT 50) and $\rho_2 = 3.9\%$ for the numerical model (Abaqus B1). The above graphs show a recurring tendency in both laboratory and numerical analysis, that is, the highest vertical displacement reduction is obtained for the CFRP tape bonded at the tensioned flange, and the highest horizontal displacement reduction is obtained for the CFRP tape applied at the compressed flange.

Unfortunately, when comparing the results of laboratory and numerical tests (Fig. 7), a significant divergence of measured values of vertical displacements is observed. Similar divergences were also found for horizontal displacement. In that case, due to large torsion, the displacement inductive gauges slipped from a preset point at the beam's walls. For example, at the load level of 16 kN, the displacement inductive sensor LVDT 200 did not touch the center of the beam's flange but slipped into the edge of the wall. Consequently, the displacement results obtained from the numerical model and laboratory tests should not be compared directly, and can be analyzed only using percentage reduction parameter with respect to the appropriate CFRP reinforcement method.

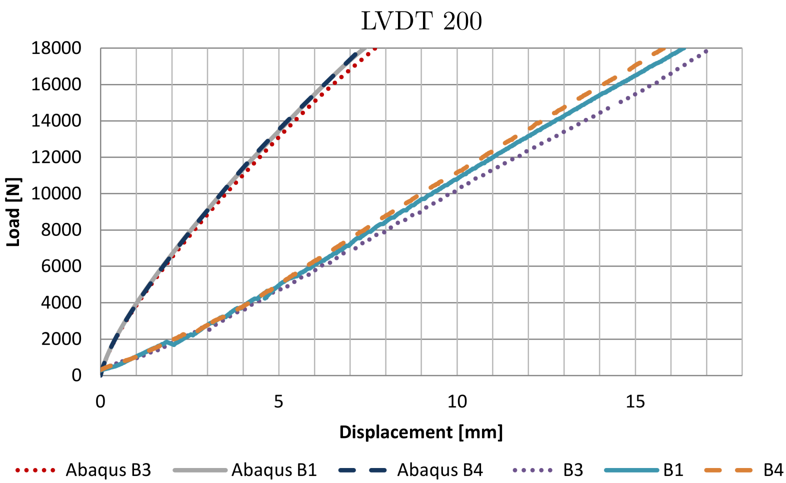

Fig. 7. The force – vertical displacement relation obtained from the numerical model and the laboratory test readout from LVDT 200.

5. Concluding remarks

The experimental research and numerical study of thin-walled steel sigma beams strengthen with CFRP tapes were performed. Based on the conducted studies, the following conclusions can be drawn:

- application of CFRP-tape reinforcement to thin-walled steel sigma beams results in reduction in strain and vertical or horizontal displacement, thus improving the stability behavior of the structure,
- application of CFRP-tape reinforcement at tensioned flange produces the strain reduction of $m_1 = 13.6\%$ (laboratory tests) and $m_1 = 17.4\%$ (numerical model), and enables vertical displacement reduction of $\rho_1 = 9\%$ (laboratory tests) and $\rho_1 = 4\%$ (numerical model),
- application of CFRP-tape reinforcement at compressed flange causes the strain reduction of $m_2 = 6.8\%$ (laboratory tests) and $m_2 = 2\%$ (numerical model), and produces horizontal displacement reduction of $\rho_2 = 10.9\%$ (laboratory tests) and $\rho_2 = 3.9\%$ (numerical model).

It should be noted that there are also quite significant differences in the strain values between the beams tested with the same CFRP reinforcement method, which may result from the geometric imperfections of thin-walled beams. Another problem is the inability to compare the results of displacement from laboratory and numerical tests. Consequently, in the next stages of research, accurate measurement of geometrical imperfections is planned to be conducted using a 3D scanner and the GOM Correlate software for digital image correlation. The numerical model should be also improved by properly modeling the adhesive layer between the CFRP tape and the thin-walled steel beam.

Acknowledgments

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References

1. Colombia P., Favaa G., Sonzogni L., *Fatigue behavior of cracked steel beams reinforced by using CFRP materials, Procedia Engineering*, **74**: 388–391, 2014.

2. Silvestre N., Camotim D., Young B., *On the use of the EC3 and AISI specifications to estimate the ultimate load of CFRP-strengthened cold-formed steel lipped channel columns*, Thin-Walled Structures, **47**(10): 1102–1111, 2009.

3. FRP International, *The Official Newsletter of the International Institute for FRP in Construction*, **1**(2), 2014, http://iifc-hq.org/wp-content/uploads/2011/01/news_vol1-issue2.pdf.

4. Ghareeb M.A., Khedr M., Sayed-Ahmed E.Y., *CFRP strengthening of steel I-beam against local web buckling: a numerical analysis*, Conference Paper, 5th International Conference on Structural Engineering, Mechanics & Computation, Cape Town, South Africa, 2013, doi: 10.1201/b15963-436.

5. Harries K.A., Peck A.J., Abraham E.J., *Enhancing stability of structural steel sections using FRP*, Thin-Walled Structures, **47**(10): 1092–1101, 2009.

6. Liu H., Xiao Z., Zhao X.L., Al-Mahaidi R., *Prediction of fatigue life for CFRP-strengthened steel plates*, Thin-Walled Structures, **47**(10): 1069–1077, 2009.

7. Liu Q., Yang J., Chan A.H.C., Li L.Y., *Pseudo-plastic moment resistance of continuous beams with cold-formed sigma sections at internal supports: a numerical study*, Thin-Walled Structures, **49** (12): 1592–1604, 2011, doi: 10.1016/j.tws.2011.08.007.

8. Miller T.C., Chajes M.J., Mertz D.R., Hastings J.N., *Strengthening of a steel bridge girder using CFRP plates*, ASCE Journal of Bridge Engineering, **6**(6): 514–522, 2001.

9. Nozaka K., Shield C.K., Hajjar J.F., *Effective bond length of carbon-fiber-reinforced polymer strips bonded to fatigued steel bridge I-girders*, ASCE Journal of Bridge Engineering, **10**(2): 195-205, March, 2005.

10. Pieńko M., Robak A., *Stand for examination of deformation of horizontal elements loaded uniformly* [in Polish: *Stanowisko do badania odkształceń elementów poziomych obciążonych równomiernie*], Zgłoszenie nr (21) 410025, Biuletyn Urzędu Patentowego, **43**(16): p. 34, 2015.

11. Różyło P., Wrzesińska K., *Numerical analysis of the behavior of compressed thin-walled elements with holes*, Advances in Science and Technology Research Journal, **10**(31): 199–206, 2016.

12. Rzeszut K., Szewczak I., *Experimental studies of sigma thin-walled beams strengthen by CFRP tapes*, International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering, **11**(7): 32–39, 2017.

13. Sayed-Ahmed E.Y., *Numerical investigation into strengthening steel I-section beams using CFRP strips*, Conference Paper, Structures Congress 2006, May 18–21, 2006, St. Louis, Missouri, United States, doi: 10.1061/40889(201)68.

14. Sayed-Ahmed E.Y., *Strengthening of thin-walled steel I-section beams using CFRP strips*, Advanced Composite Materials in Bridges and Structures, Conference Paper, 4th International Conference on Advanced Composite Materials in Bridges and Structures (ACMBS IV), Calgary, Alberta, Canada, 2004.

15. Szewczak I., Rzeszut K., *Pilot experimental studies of thin-walled Sigma steel beams reinforced with CFRP tapes* [in Polish: *Pilotażowe badania eksperymentalne cienkościennych belek stalowych typu sigma wzmocnionych taśmami CFRP*], Materiały Budowlane, **531**(11): 84–85, 2016.

16. Waszczyszyn Z., Cichon CZ., Radwanska M., *Stability of structures by finite element methods: Volume 40*, Elsevier Science B.V., 2013.

17. Zhao X.L., Al-Mahaidi R., *Web buckling of lightsteel beams strengthened with CFRP subjected to end-bearing forces*, Thin-Walled Structures, **47**(10): 1029–1036, 2009.

18. Zienkiewicz O.C., Taylor R.L., *The Finite Element Method*, Volume 2: Solid Mechanics (5th Ed.), Butterworth-Heinemann, 2000.

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