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Study of Carbon Fiber Reinforced Polymer Composite Layer Structures Subjected to Three-Point Bending

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ABSTRACT

The development of new composite and structural materials in various areas of industry has led to an ever-growing interest in research results regarding the applications of these materials. Combining these materials allows for the modification of the strength characteristics of structures and components manufactured from them. The article presents the results of bending test of carbon fibre reinforced polymers (CFRP) strips bonded with a two-component epoxy adhesive. Additionally, the reinforcement effect resulting from gluing composite strips (multilayer reinforcement) was compared with shortened strips. The positive and negative influences of shortening strips unidirectionally reinforced with long fibre have been discussed. Differences in the stiffness of the tested belt systems indicate that adding another belt increases the load capacity by approximately 100% of the bending force compared to the previous test of fixed-length belts. TSP tapes also show an increase in the ability to transfer the bending force by gluing subsequent strips, but not necessarily along the entire length, as shown in tests. Simulation tests showed smaller displacement compared to physical samples. The smallest differences between measurements and simulation results were recorded for two-layer configurations, while the largest differences were observed for four-layer strips.

Keywords: composite tapes, epoxy adhesives, carbon fibre.

INTRODUCTION

Nowadays, technological progress is inextricably linked to material engineering that deals with the creation of new materials, which includes composite materials that significantly affect the development of various industries.

These materials are considered a leading group that can shape the future of not only the automotive or construction industries, but also the medical, metallurgical and food industries. Composites are materials with different and complementary mechanical, physical and chemical properties. They often significantly exceed the strength properties of classic materials [1–5]. Synthetic strips and composite materials are one of the most commonly used materials for reinforced structures such as bridges, pillars, car bodies (automotive industry) or aircraft components (aerospace industry) [6–9]. These materials have a special impact due to changes in the approach to the design of modern car bodies and the plating of wide-body aircraft, where the ratio of weight to strength is significant during the operation thereof. In recent years, synthetic strips have been used in construction to strengthen the load-bearing structures of building structures such as chimney shafts [10, 11], reinforced concrete spans [12–14], steel structure elements, which include railway facilities, road facilities, footbridges, wooden structure elements [15–24] and many others [25–33]. Most often the aforementioned industries use CFRP

– carbon fibre strips in an epoxy matrix, where their main advantages are high tensile strength, very high fatigue strength, corrosion resistance, the ability to cross strips, small transverse dimension and low weight [34, 35]. Connecting the strip with a reinforced element occurs through contact connections (mainly gluing). Strengthening concrete and steel structures by gluing composite strips, as an external reinforcement, belong to a very rapidly developing method on a global scale, however, it is still hardly recognized mainly due to the very wide application possibilities. The scope of publications from this thematic area is growing, yet research in the field of strengthening structures by sticking strips is explored in a very narrow scope. Therefore, the subject of this publication is to present the results and works on the possibilities of producing laminated glued structures and analysis of the mechanical properties thereof.

PREPARATION OF SAMPLES AND MATERIALS USED

The test programme included determination of the strength of the bent samples of multilayer constant and progressive length strips. In order to perform the tests, the samples were made of commercial composite strips from S&P C-Laminate (Fig. 1) and two-component epoxy adhesive from Araldite 2021–1 (Fig. 2). The strips are a flat structure of continuous carbon fibre (roving)

Figure 1. CFRP tape from S&P Polska

Figure 2. ARALDITE 2021–1 two-component adhesive application system, static mixer, 50 ml cartridge and glue application gun

in a matrix of polymeric chemosetting resin with a cross-section of 20x1.4 mm and a modulus of elasticity E = 210 GPa. The general properties of the fibre used in the strips according to the manufacturer are given in Table 1.

Two series of samples were prepared: continuous, marked as T (where each strip of the layer had the same length of 150 mm, Fig. 3) and progressive samples marked as TS (where each subsequent layer was shorter than the previous one, from 150 mm to 60 mm, Fig. 4).

Table 1. Physical properties of the fibre used in S&P C-Laminate strips

Physical properties	Unit	Value
Density	g/cm³	1.6
Fibre volume content	% Vol.	> 68
Tensile strength	N/mm²	≥ 2 800
Elongation at break	‰	> 13.5

The samples were purified with technical acetone and glued. In order to achieve the most accurate repeatability of the samples, glue was used in 50 ml cassettes applied by means of a dosing system equipped with a static mixer (Fig. 2).

Gluing was carried out at room temperature 23 °C and with humidity of approximately 50%. After the adhesive was applied, the glued elements were pressed with a weight, the excess adhesive was collected with a spatula and the samples were left until the adhesive set according to the manufacturer's instructions. After conditioning during 72 hours, three-point bending tests were carried out on a Hegewald & Peschke testing machine – frame 20 (Fig. 5).

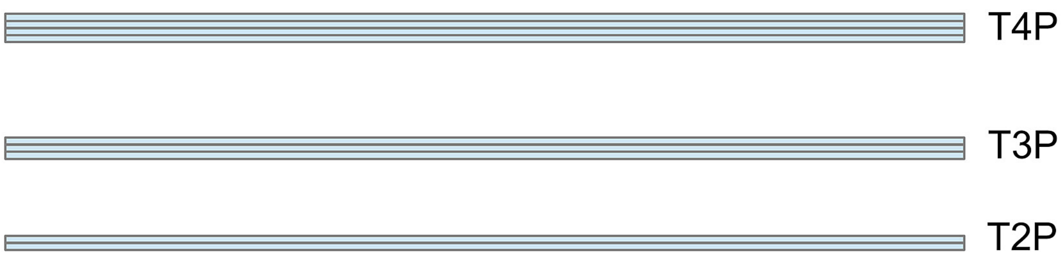

Figure 3. Scheme and determination of fixed length samples

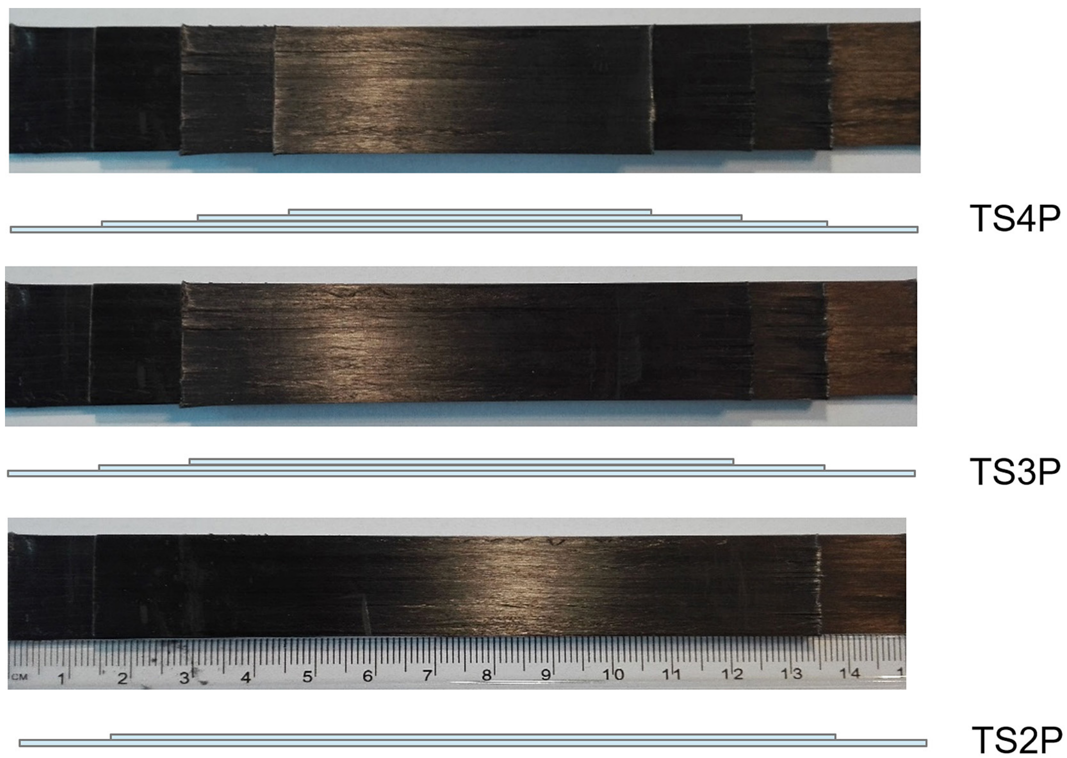

Figure 4. Scheme and designation of progressive samples, where: T– CFRP strip, S – sample with shortened CFRP strip, number (L) – denotes the number of strips

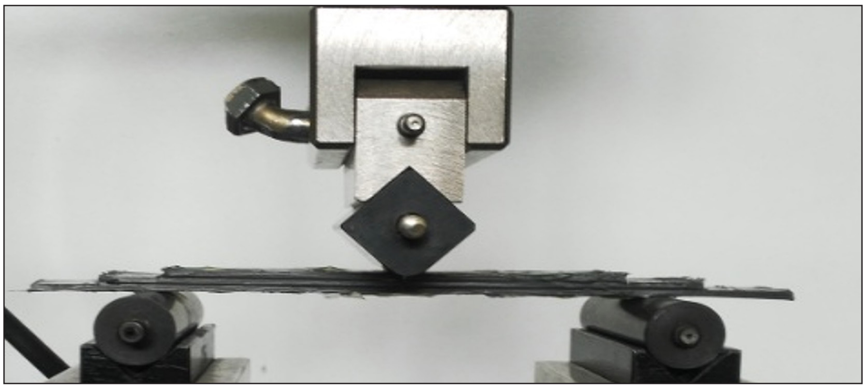

Figure 5. Sample mounted in the three-point bending holder

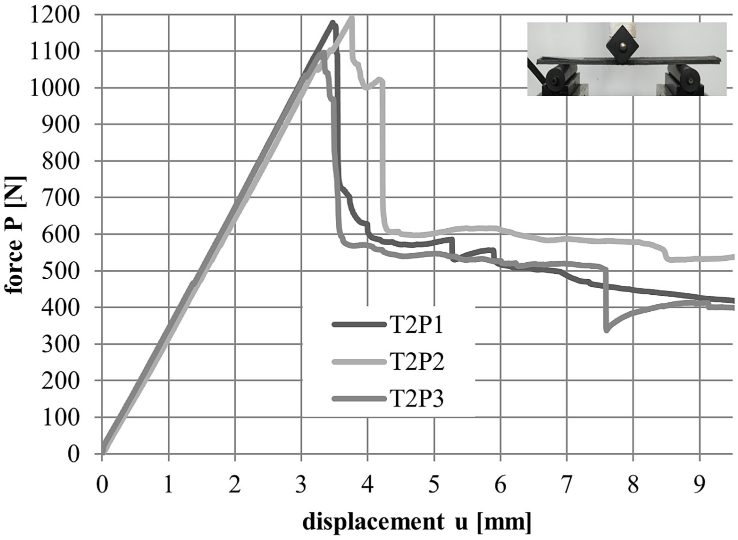

Figure 6. The relationship of force P as a function of displacement u for the T2 series

Three series of samples of each type T and TS were prepared. The samples prepared in this way were bent on the testing machine. The samples were bent according to the guidelines contained in the PN-EN ISO 178: 2011 standard. The spacing of the supports was 100 mm, the traverse movement speed was 5 mm/min. The results of the tests are presented in the form of graphs in Figures 6–11.

BENDING TEST RESULTS FOR T-SERIES SAMPLES

The T2P samples reach a maximum force of approximately 1 200 N, in addition, the jumps in the graph illustrate the points of loss of adhesive adhesion with carbon fibre strips. Increasing the number of strips causes an increase in bending force in the T3P samples by almost 99%, which is shown in Figuew 7, additionally the sample stiffens, which results in a decrease in deflection at the place of maximum force by approx. 1mm compared to deflection in the T2P samples. After gluing the next strip, the element stiffens and displacement is reduced. The course of force changes as a function of the displacement of individual series of the samples is similar, which suggests that the samples were prepared correctly and carefully.

BENDING OF TS SERIES SAMPLES

Progressive length TS2P samples reach a maximum force of 1 400 N, the jumps on the graph, as in the case of the T2P series samples, indicate the loss of adhesion between the strips. Increasing the number of strips (TS3P series) causes a bending force increase of 65% and a reduction of displacement by more than 1 mm compared to the TS2 series. Attaching another strip (series TS4P) does

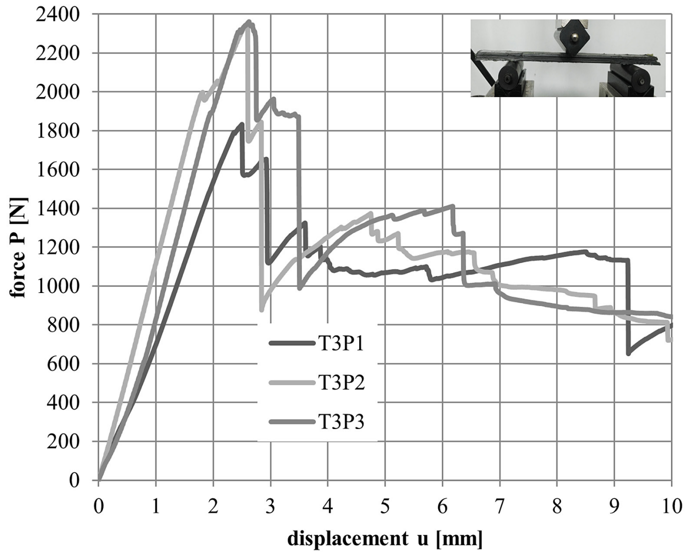

Figure 7. The relationship of force P as a function of displacement u for the T3 series

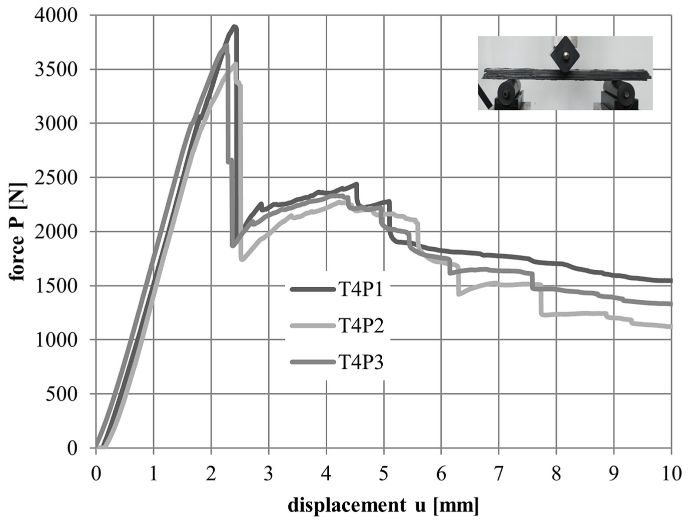

Figure 8. The relationship of force P as a function of displacement u for the T4 series

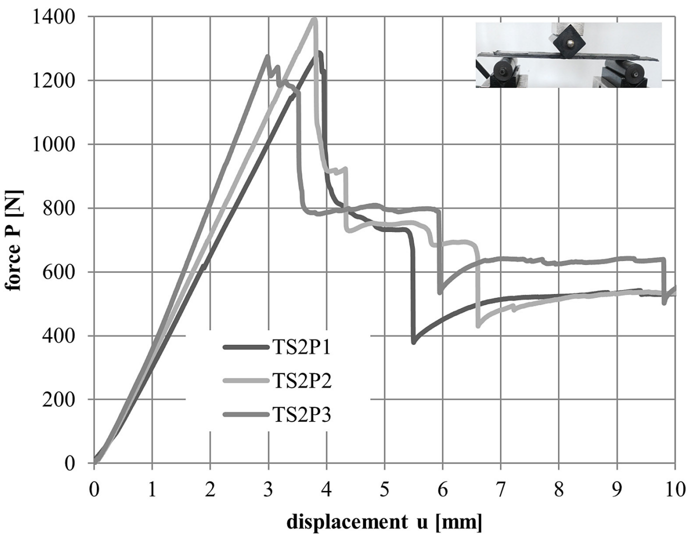

Figure 9. The relationship of force P as a function of displacement u for the TS2 series

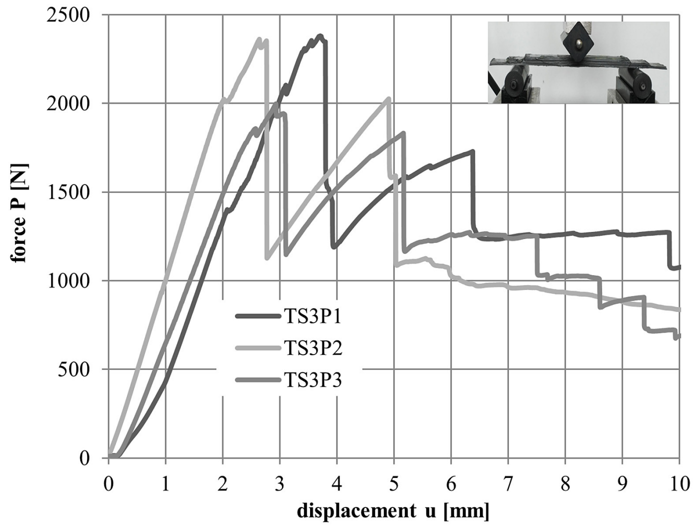

Figure 10. The relationship of force P as a function of displacement u for the TS3 series

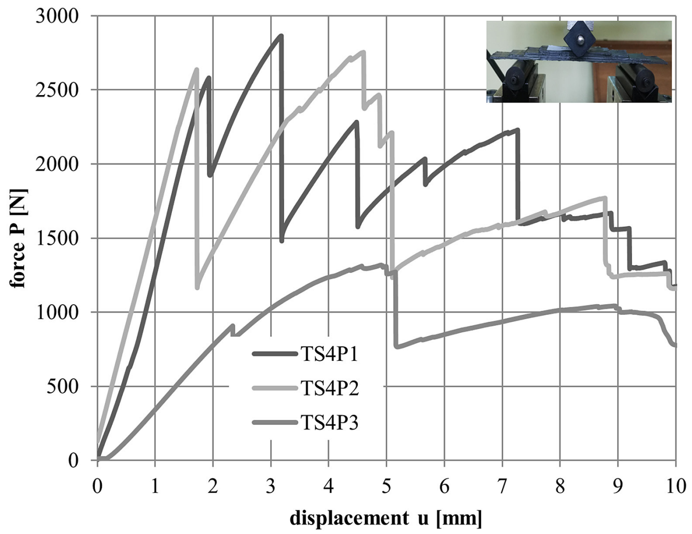

Figure 11. The relationship of force P as a function of displacement u for the TS4 series

not translate into an increase in the transmission of bending force compared to the previous series. It was also observed that in the TS4P series one of the samples clearly differs from the others, the reason for this may be an uneven distribution of the adhesive or careless preparation of the sample. In further analysis, the last sample was rejected for the above-mentioned reasons.

DISCUSSION OF RESULTS

For the analysis of the stiffness of the layered structures, a displacement range (deflection) of 0.5; 1; 1.5 and 2 mm was used, where the bending took place in a linear-elastic manner. The mean values from all tests of each type of connection were compared. The results are presented in pairs for individual deflection values of the continuous T-series and the progressive TS-series samples (Figs. 12–14). The percentage differences between individual samples are presented in Table 2. As can be seen from Figs. 12–14, adding subsequent strips to the TP samples results in an increase in load capacity by approximately 100% of the bending force compared to the previous test of fixed length tape. The TSP tapes also show an increase in bending force transmission by gluing subsequent strips, as shown in Figs. 12-14 and Table 1. Comparing the TP strips with the TSP strips, it can be seen that for the T2P and TS2P tests, the percentage difference in bending force

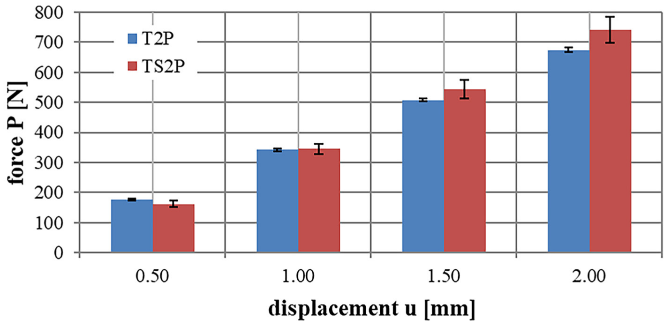

Figure 12. Comparison of P force values in T2P and TS2P for assumed displacement values u = 0.5; 1; 1.5 and 2 mm

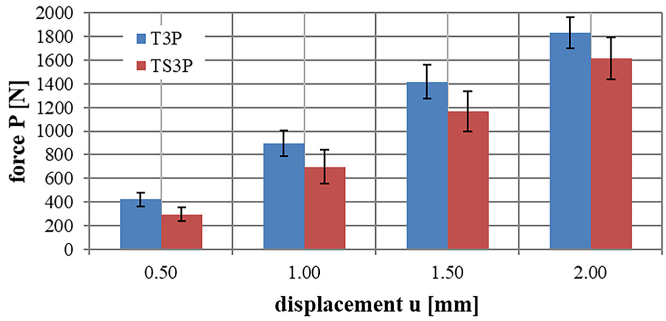

Figure 13. Comparison of P force values in T3P and TS3P strips for assumed displacement values u = 0.5; 1; 1.5 and 2 mm

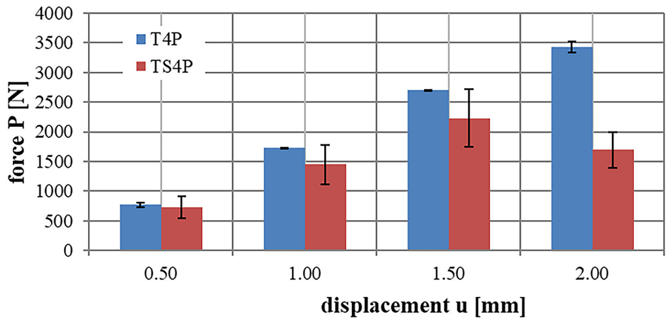

Figure 14. Comparison of P force values in T4P and TS4P strips for assumed displacement values u = 0.5; 1; 1.5 and 2 mm

Table 2. Comparison of force values in fixed length adhesive strips (T series) with progressive length adhesive strips (TS series)

Connection type	Displacement [mm]			
	0.5	1.0	1.5	2.0
	Force [N]			
T2P	175.71	341.48	507.02	674.33
TS2P	161.68	344.91	543.52	741.54
Percentage difference [%]	9	1	7	9
T3P	422.95	896.17	1 415.99	1 830.44
TS3P	295.64	697.87	1 164.56	1 612.98
Percentage difference [%]	43	28	22	13
T4P	772.19	1 728.27	2 695.93	3 423.76
TS4P	726.57	1 448.86	2 231.25	1 691.91
Percentage difference [%]	6	19	21	102

for individual deflections (displacements) is negligible and even goes in favour of the TS2P strips. It can therefore be assumed that there is no need to glue the second layer of strips over the entire length of the element.

Analysing the T3P and TS3P and T4P and TS4P strips, it can be observed that there is a decrease in the bending force transmission in TSP strips compared to TP strips. Most likely, the difference is due to the surfaces of the composite strips joined together. The larger the surface, the greater the adhesive forces between the individual strips. In the TSP strips, the surface between individual layers was shortened, which meant that the glued surface was smaller and higher stresses were created than with the anthological connection of the TP strips, where the adhesive surface was along the entire length of the strip. However, the differences between the T3P and TS3P samples are so satisfactory (with a 2 mm deflection, the difference was only 13%) that with the need for a slight strengthening of the element, such a solution would reduce the cost of strip and glue while increasing the strength of the element by more than 100% compared to the T2P or TS2P tests.

NUMERICAL ANALYSIS

Simulation tests were performed using MES ADINA System software. The finite elements had dimensions of 0.1 × 0.1 mm. A 2D analysis was used taking into account the width of the belt. The simulated strip a had a Young's modulus of 210000 MPa and a Poisson's ratio of 0.3. Additionally, the Young's modulus for the adhesive was assumed to be 1000 MPa and the Poisson's ratio was 0.4. An exemplary model of the TS4P belt is shown in Figure 15. Figures 16–21 present selected results of the three-point bending analysis of the belts: the relationship between the applied force and the

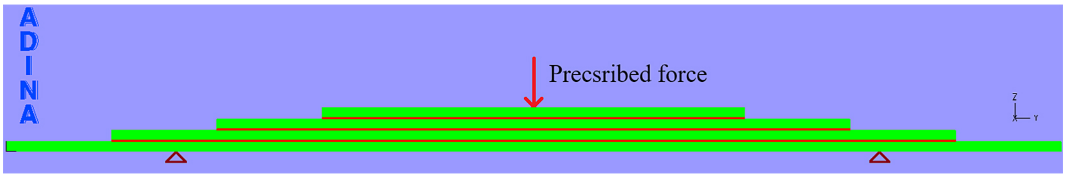

Figure 15. Numerical model of TS4P sample

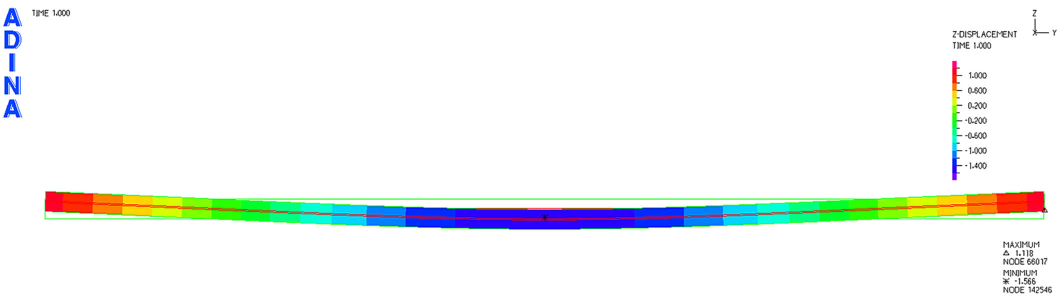

Figure 16. Displacement of the T2P strips with a load of 674.33 N

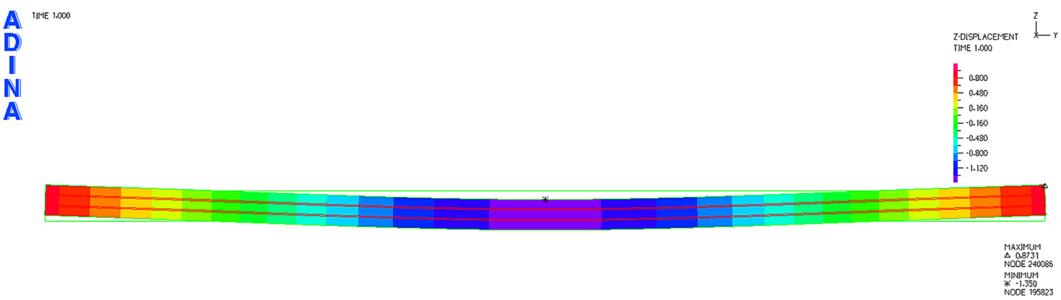

Figure 17. Displacement of the T3P strips with a load of 1830.44 N

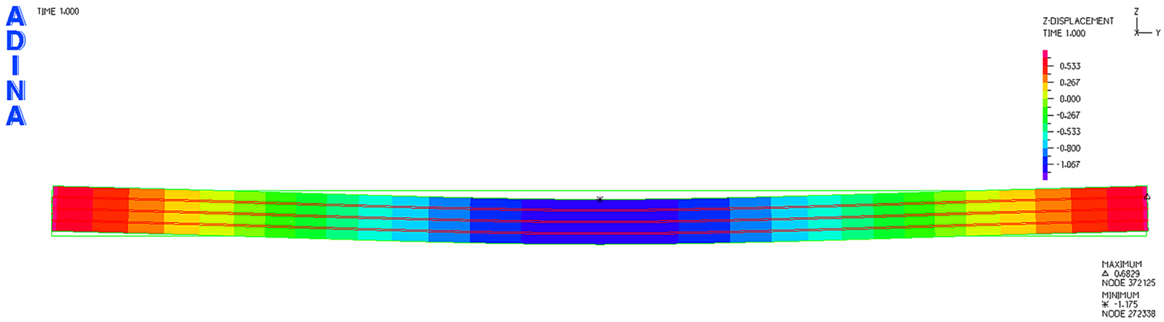

Figure 18. Displacement of the T4P strips with a load of 3423.76 N

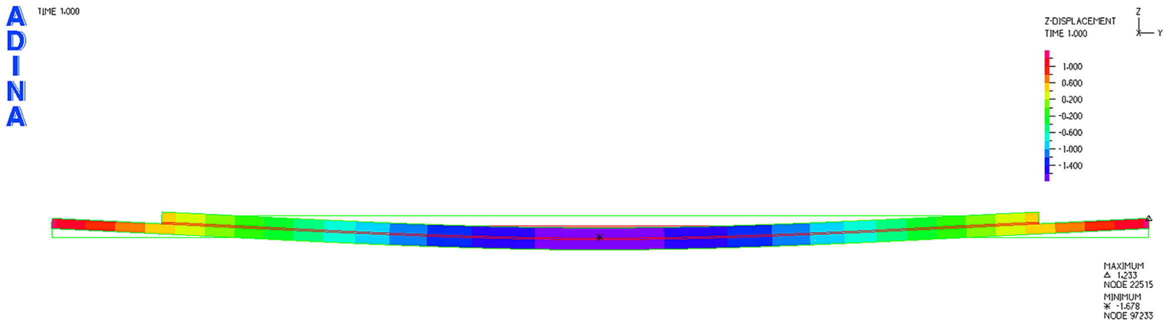

Figure 19. Displacement of the TS2P strips with a load of 741.54 N

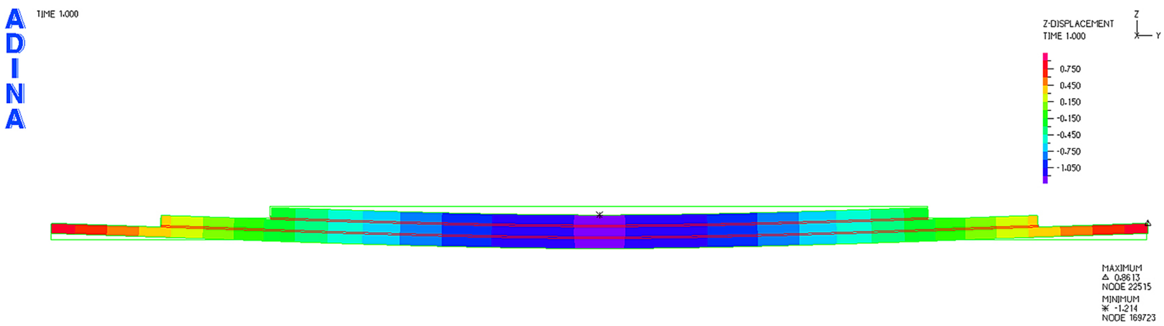

Figure 20. Displacement of the TS3P strips with a load of 1612.98 N

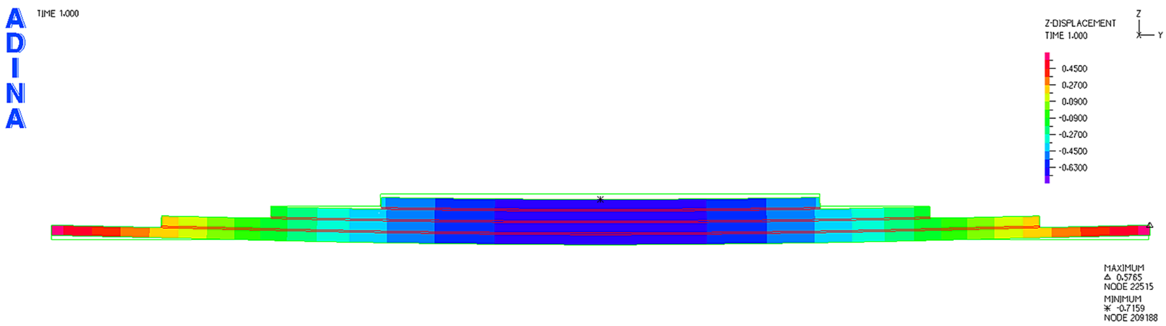

Figure 21. Displacement of the TS4P strips with a load of 1691.91 N

displacement in the Z axis. The force values presented in Table 2 were adopted. As a result, the displacement was achieved. The simulation model will therefore make it possible to compare the displacement results with the values obtained on physical samples. Due to the volume of work, only the results for maximum forces are shown. A comparison of all results is presented in Figure 22.

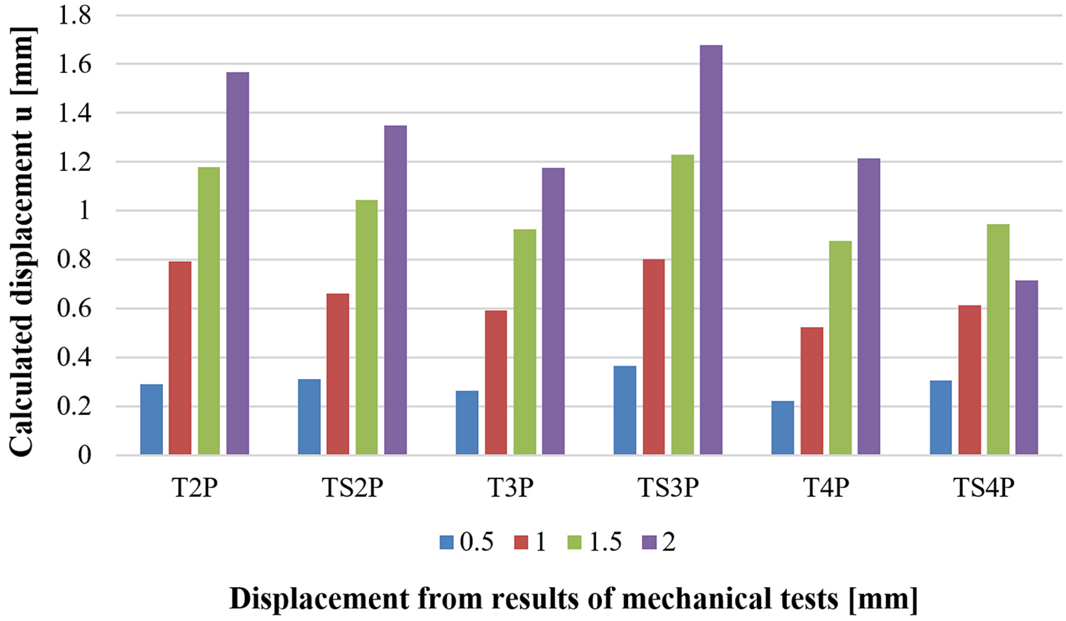

Figure 22. Comparison of sample displacements depending on the applied force, in relation to physical samples

CONCLUSIONS

Strengthening with carbon strips is one of the most commonly used methods to increase the strength properties of load-bearing structures. This treatment is primarily intended to reduce deflection, cracks or increase the load capacity of existing structures. Strips are placed in the zones of the tension bearing elements. Bonding is carried out using adhesives based on epoxy resins. The analysis of the conducted tests showed that the reinforcement behaviour depends on the preparation of the surface of the glued elements. This avoids damage caused by loosening or delamination, or even weaker results of increasing the load capacity of a given element. The most effective configuration turned out to be the TS2 sample series, where the percentage differences are negligible and favourable for progressive samples. Similar results are obtained by the TS3P and TS4P series, the forces transferred by these series are slightly smaller than the samples combined on the entire surface. Further analysis showed that progressive length strips, up to three layers, can be used for secure reinforcement, after a careful risk and benefit analysis. The use of progressive strips for multi-layer gluing reduces the costs of strengthening a given structure while increasing its serviceability.

The next stage will be a microscopic analysis of the damage mechanism of individual layers and adhesive joints between these layers. Further work is aimed at developing appropriate design criteria and selecting the number and length of progressive strips. It is necessary to create a model for calculating stresses at critical locations, places of concentration and discontinuities, and then predicting the forms of destruction of individual layers and the entire reinforcement.

Based on the research, it can be seen that the values of displacements in the Z axis obtained from numerical simulations differ slightly from real measurements. The smallest differences between measurements and simulation results refer to two-layer strips and amount to approximately 0.2 mm, while the largest differences, up to 0.8 mm, refer to four-layer strips. In general, simulation tests showed smaller displacements compared to physical samples. This may be caused by imperfections resulting from gluing the strips and some inaccuracy related to the finite element method.

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