Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal, 2025, 19(12), 394–401
https://doi.org/10.12913/22998624/209888
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Received: 2025.07.31
Accepted: 2025.10.01
Published: 2025.11.01

Use of carbon fiber fabric for reinforcement of bent hot-rolled steel channels

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ABSTRACT

The widespread application of steel as a structural material in industrial and bridge construction highlights the importance of research into strengthening methods for steel structures made of hot-rolled profiles. This study presents laboratory tests conducted on bent hot-rolled C100 steel channels with a length of 3 meters. A total of eight beams were tested, of which the first two served as unstrengthened reference specimens. The remaining beams were reinforced using bonded carbon fiber fabric in three different configurations. The results of the experimental study indicate a negligible effect of this strengthening method on the increase in ultimate load capacity and strain reduction, while showing an approximate 22% reduction in horizontal displacements compared to the reference beams.

Keywords: strengthening, carbon fiber fabric, hot-rolled steel channel.

INTRODUCTION

The widespread use of steel as a structural material in both industrial buildings (e.g., halls, shelters) and bridge construction justifies the need for research aimed at developing strengthening methods for steel structures made of hot-rolled sections. A review of the literature reveals a number of publications devoted to this subject. One of the most common strengthening techniques involves welding additional steel components to existing structural elements. For instance, reference [1] describes tests on strengthening steel I-beams under bending using welded reinforcements. In [2], the strengthening of compressed steel tubular columns with welded steel angles is presented, while [3] covers experimental and numerical investigations of a composite beam (a steel I-beam connected to a reinforced concrete slab) subjected to loading and strengthened by welding an additional plate to the bottom flange of an IPE section.

Research has also focused on the execution of welded joints and the impact of replacing continuous welds with intermittent welds [4]. Strengthening through welding, using steel plates, flat bars, or other profiles, is a widely adopted method in practice due to the availability and relatively low cost of materials. Additional advantages include the uniformity of mechanical properties between the strengthening and strengthened materials, as well as ease of mechanical processing. However, this technique also has several drawbacks: the handling and transportation of heavy plates, limited material lengths requiring additional joints, and the risk of corrosion. Moreover, welding is not suitable for structures located in environments with high fire hazards. One must also consider that welding an existing structure introduces uncontrolled welding-induced stresses. The heat input causes irreversible deformation of the structural geometry. The strengthening method should account for this and aim to minimize these effects. Strengthening truss systems by welding additional members to existing ones should preserve the symmetry of individual members and the overall structural symmetry in the plane of the truss [5].

Another method of strengthening steel structures involves riveting. Once a common technique [6], riveting is now rarely addressed in contemporary research, though there are some studies on strengthening riveted truss joints with additional rivets [7], or comparing the strength of welded and riveted connections [8].

The aforementioned methods are invasive, as they either introduce additional welding-induced stresses or require the creation of holes for mechanical connectors. For this reason, considerable interest has arisen in the use of fiber-reinforced polymer (FRP) composites bonded to steel structures as a strengthening technique. Current literature is dominated by research on bonded CFRP (carbon fiber-reinforced polymer) strips with varying cross-sectional dimensions and mechanical properties. The application of CFRP strips significantly reduces deflections and strains in hot-rolled steel I-beams subjected to bending [9–10], as well as in hollow sections [11] and plates [12–13]. CFRP strips can be bonded passively or post-tensioned using appropriate installation methods [14]. As demonstrated in [15], the use of CFRP strips also significantly improves the fatigue strength of tested steel specimens. Even research has been carried out on the influence of the shape of the CFRP/steel joint end on the behavior of hot-rolled bent steel elements [16], which indicates a wide scope of research on the use of composite tapes. Composite materials can also be successfully used to reinforce cracked reinforced concrete elements in which the reinforcing steel is damaged by corrosion [17]. In addition to laboratory tests, analytical and numerical studies are also available regarding the design of FRP-strengthened steel members [18].

A broader review of research on strengthening steel structures is presented in [19]. Reference [20] not only provides an updated literature review but also discusses the limitations of FRP strengthening (e.g., environmental conditions) and proposes predictive methods for evaluating performance under various loading and environmental scenarios, enabling safe and reliable design of FRP-strengthened steel structures.

To date, no studies have been found on strengthening hot-rolled steel C-channels under bending, even though such sections are commonly used – for example, as purlins in steel halls. Most publications focus on CFRP strips, while carbon fiber fabrics – commonly used in concrete structural strengthening – are rarely considered. Therefore, this study investigates the effectiveness of strengthening bent hot-rolled steel C-channels using carbon fiber fabric.

TEST PREPARATION

Eight specimens made of hot-rolled C100 channels from S235 structural steel, each 3 meters in length, were subjected to four-point bending tests. The detailed cross-sectional dimensions of the test specimens are provided in tab. 1, with corresponding notations illustrated in Figure 1a.

The specimens were divided into four groups. The first two specimens served as reference samples, designated as BR1 and BR2 (Figure 1b). The remaining six specimens were strengthened by bonding a carbon fiber fabric (SikaWrap®-230 C) using an epoxy adhesive (SikaDur®-330). Specimens labeled BMK1 and BMK2 were reinforced by applying a 170 cm

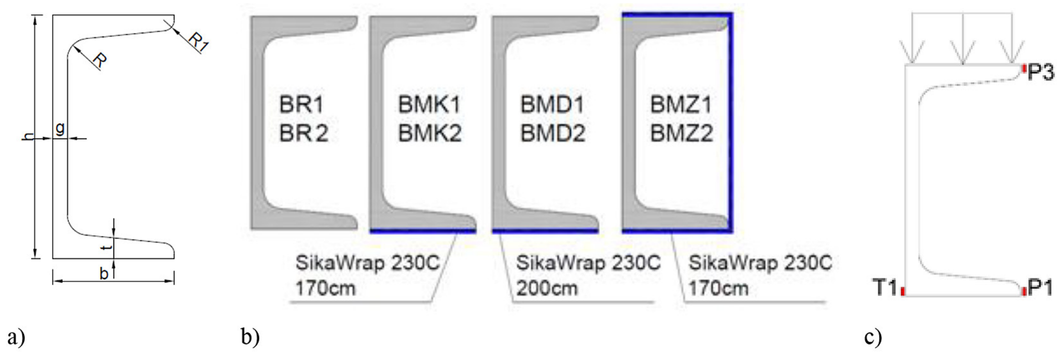


Figure. 1. a) designation of the dimensions of the cross-section of the tested channel, b) nomenclature of the groups of tested beams and the method of reinforcement, c) location of the measurement points

Table. 1. Cross-sectional dimensions of the C100 channel section

Symbol	h	b	g	R	R1	t	A
	[mm]						[cm^2]
C100	100	50	6	8.5	4.5	8.5	13.5

long strip of fabric across the full width of the bottom flange of the channel section. In specimens BMD1 and BMD2, the strengthening fabric was also applied to the underside of the bottom flange, but with a length of 200 cm. In each case, the carbon fibers were aligned parallel to the longitudinal axis of the tested specimen.

The last two specimens, designated BMZ1 and BMZ2, were strengthened using a closed-section reinforcement configuration (Figure 1b), with the fabric bonded to both the upper and lower flanges of the channel section. In this configuration, the reinforcement was applied over a length of 170 cm, with the carbon fibers oriented perpendicular to the longitudinal axis of the specimen.

Prior to the strengthening process, all tested beams were cleaned and abraded using sandpaper, followed by degreasing with extraction gasoline. Subsequently, the SikaDur®-330 adhesive was applied to the selected bonding surfaces, and the SikaWrap®-230 C fabric was placed onto the adhesive layer. Using a roller, care was taken to ensure complete impregnation of the carbon fibers into the adhesive layer.

Mechanical properties and technical data for SikaWrap®-230 C and SikaDur®-330 are available in the respective product datasheets provided by the manufacturer [21–22].

Laboratory testing commenced at least 7 days after the bonding process, allowing the adhesive (SikaDur®-330) to fully cure and reach its specified mechanical properties.

Then, a T1 electrical resistance strain gauge was placed on all samples in the middle of their span (the exact location of the strain gauge is shown in Figure 1c) and measuring points were glued to measure displacements using the Aramis optical system. This study analyzes displacements at measurement points P1 and P3, both located at the mid-span of the beam, as shown in Figure 1c and Figure 2.

LABORATORY TESTS

Four-point bending tests were conducted on a Zwick&Roel testing machine (ZwickRoell GmbH & Co. KG, Ulm, Germany) in the construction laboratory of the Lublin University of Technology. Load was generated by moving the press piston at a speed of 3 mm/min, recording load increments every 0.01 s. The tested beams were placed on specially prepared supports spaced 270 cm apart. The value of relative slenderness to lateral-torsional buckling for the analyzed beams (λLT) determined on the basis of formula (6.56)

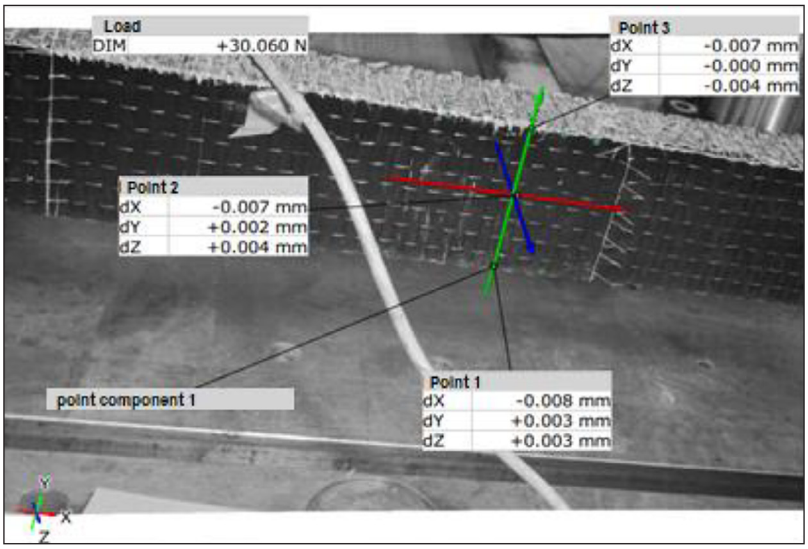


Figure 2. Location of points for displacement measurement using the Aramis system

from EN 1993-1-1:2005+AC:2006 is 0.903. The supports only prevented displacement of the beams at the support point along the Y and Z axes (see the axis arrangement in Figure 2). The spacing of the press load application points was 135 cm. The beam length chosen was due to the limitations of the laboratory setup (beams 3000 mm long are the longest elements that can be loaded in the press used for testing). The spacing of the supports and load application points was selected so that the bending moment value at the mid-span of the beam was the same as that for a uniformly distributed load. After placing the beam on the test stand, connecting the strain gauges, and calibrating the Aramis system, it was loaded in the testing machine until failure. During the test, TENMEX TFs-10 120Ω ± 0.2% electrical resistance strain gauges were used to measure deformations, while the Aramis optical system was used to measure displacements at the indicated control points (which allowed for 3D measurement of beam displacements). A photograph and diagram of the test stand are shown in Figure 3.

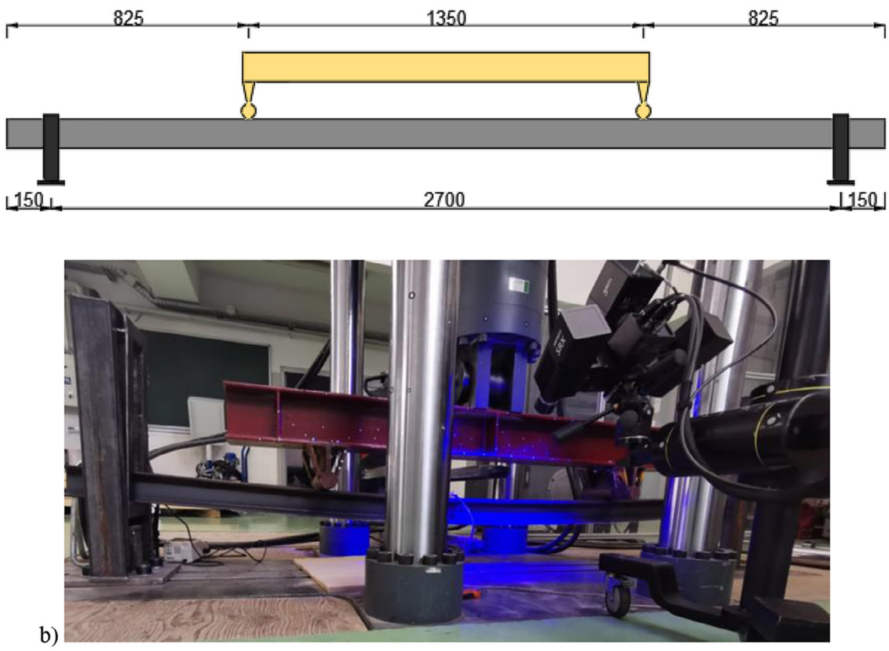
All samples exhibited the same failure mode. As a result of the applied load, the channels experienced bending and twisting, which results from the displacement of the cross-section's center of torsion relative to the center of the channel flange width. The behavior of the beams under load and the mode of failure are shown in Figure 4. During laboratory testing, no fabric SikaWrap®-230 debonding was observed in any of the reinforced beams (a common occurrence when CFRP composite tapes were used for reinforcement).

LABORATORY TEST RESULTS

During the laboratory testing, displacements at the mid-span of the channel section were measured at points P1 and P3, and strains were recorded using an electrical resistance strain gauge (T1) on all tested beams. The beams were loaded until failure. The applied strengthening method contributed to an increase in ultimate load capacity in only two beams: BMD1 (by 3.2% relative to the average failure load of the two reference beams) and BMK2 (by 2.1% relative to the average failure load of the two reference beams). The ultimate load values obtained for each beam are presented in table 2.

Based on the values presented in Table 2, it can be concluded that the application of carbon fiber fabric (SikaWrap®-230) reinforcement does not contribute to an increase in ultimate load-bearing capacity. Similarly, in studies concerning the strengthening of axially compressed steel angle sections [23], the use of carbon fiber fabric (SikaWrap®-230) resulted in only a slight increase in the ultimate load (by 4.3%) compared to the reference specimens. This effect was significantly lower than the results achieved using

a)



b)

Figure 3. The schematic (a) and photograph (b) of the test stand

Figure 4. The photos of a) the work of beams under the influence of load in the press, b) the method of destruction of the tested beams

steel strip reinforcement (38.2%) and CFRP strips (28.3%) bonded with SikaDur-30 adhesive.

The strain measurement results at the location of strain gauge T1 are presented in Figure 5. The vertical and horizontal displacements at point P1 (with respect to the Y and Z axes, see Figure 2) are shown in Figure 6. Due to the large number of test specimens and limited clarity of the graphical results, Table 3 has been compiled to present the displacement and strain values under a load level of 40 kN. This load level was selected for the analysis of the strengthening effects because all tested beams reached this ultimate load, and at higher load levels, the graphs exhibit discontinuities caused by beam slippage at the support, which could render the selected results unreliable. The table initially presents the displacement results at measurement points 1 and 3, as well as the strain results for each beam. The second part of the table then presents the displacement and strain results for a given series of samples (calculated as an arithmetic mean) to help draw the final conclusions.

Analyzing the effect of carbon fiber fabric (SikaWrap®-230) reinforcement on strain reduction at the T1 strain gauge location (at a load level of 40 kN), it was found that placing a 200 cm section of fabric on the bottom flange of the channel section proved most effective, reducing strain by 3.6% compared to the reference beams. A slightly smaller reduction in strain was achieved after reinforcing the cross-section of the tested channel section (2.7%), while the effect of reinforcing with a 170 cm section of fabric placed at the bottom of the bottom flange proved negligible. It should be added that the reinforcing material lengths of 170 cm and 200 cm were selected based on previous laboratory tests on the strengthening of thin-walled cold-formed steel beams (research on effective anchorage length). In those tests, a reinforcing

Table. 2. Ultimate load capacity of individual beams and average failure loads for each beam series.

Beam symbol	Destructive force [N]	Average value of the destructive force in a given series [N]
BR1	45667	45479,5
BR2	45292	
BMD1	46937	45559,5
BMD2	44182	
BMK1	44015	45229
BMK2	46443	
BMZ1	44872	44745
BMZ2	44618	

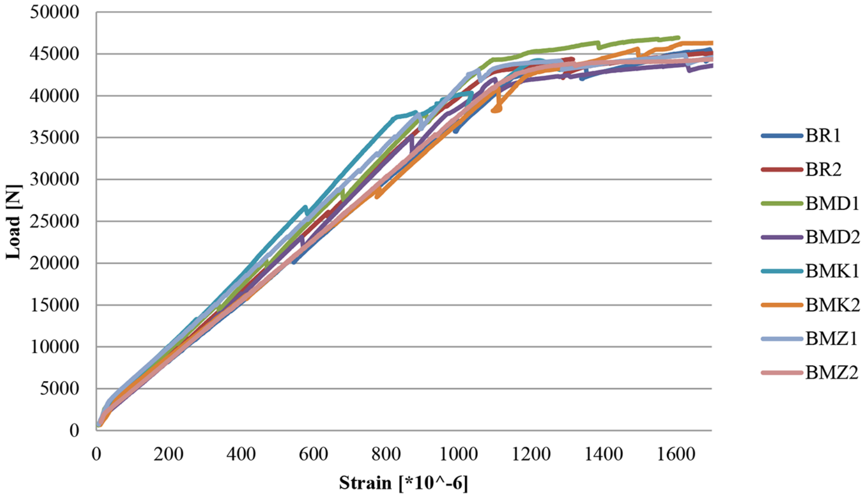
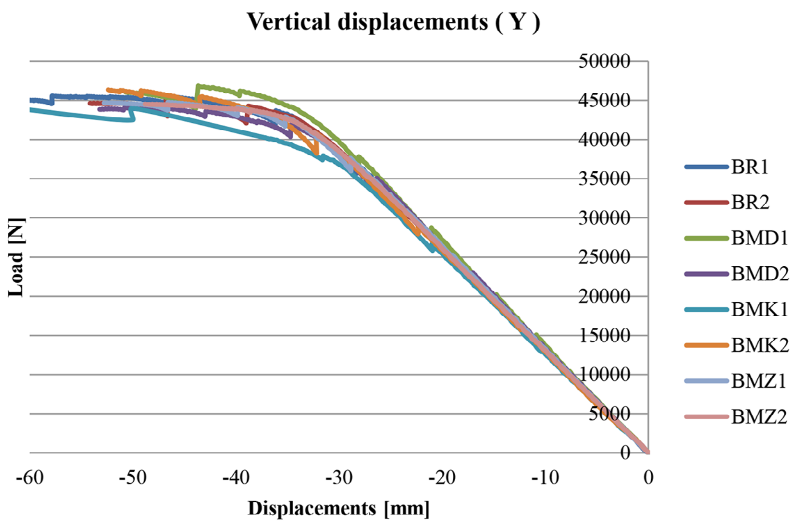
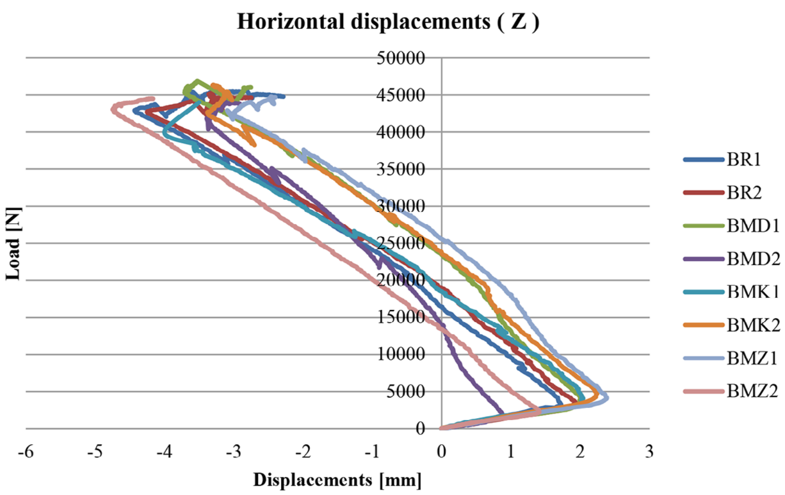


Figure 5. Load-strain relationship graph for the tested beams



a)



b)

Figure 6. Load-displacement relationship graph for the tested beams a) in the vertical direction relative to the Y axis, b) in the horizontal direction relative to the Z axis

Table. 3. Values of displacements and strains of beams at a load of 40 kN

Beam symbol	Strain [·10^{-6}]	Displacements [mm]				Strain – arithmetic mean value for a given series [·10^{-6}]	Displacements – arithmetic mean value for a given series [mm]			
		Point 1 (dy)	Point 1 (dz)	Point 3 (dy)	Point 3 (dz)		Point 1 (dy)	Point 1 (dz)	Point 3 (dy)	Point 3 (dz)
BR1	1095	-31,53	-3,83	-32,01	5,01	1050	-31,37	-3,74	-31,86	5,06
BR2	1005	-31,20	-3,66	-31,72	5,10					
BMD1	977	-30,16	-2,61	-30,64	5,58	1012	-31,03	-2,91	-31,55	5,81
BMD2	1047	-31,90	-3,22	-32,47	6,04					
BMK1	1007	-36,38	-3,92	-37,27	8,32	1046	-34,86	-3,43	-35,61	7,65
BMK2	1085	-33,34	-2,94	-33,95	6,98					
BMZ1	977	-31,95	-2,54	-32,51	6,88	1022	-31,71	-3,38	-32,25	6,03
BMZ2	1067	-31,47	-4,22	-31,99	5,17					

material length of 170 cm proved optimal – increasing the length of the composite tapes no longer reduced the displacements and strains in the analyzed beams (which is not confirmed in this article). Comparing the displacement results obtained during laboratory tests for individual beam series, it was found that the use of carbon fiber fabric (SikaWrap®-230) resulted in slight reductions in displacement compared to the results obtained with the reference samples in the vertical direction only in the case of the BMD beam series (by approximately 1.1% at both measurement points). In the horizontal direction (relative to the Z axis), the applied reinforcements reduced displacements only at measurement point number 1. Again, the most favorable result was achieved by using a 200 cm long reinforcement on the lower flange of the channel (by over 22% compared to the reference beams). In the remaining beam series, the applied reinforcement contributed to reducing displacements in this direction by approximately 9%.

CONCLUSIONS

The laboratory tests presented in this paper allow us to draw the following conclusions:

- the use of carbon fiber fabric (SikaWrap®-230) reinforcement does not increase the ultimate force in bending tests on hot-rolled channels;
- analyzing the effect of composite fiber fabric reinforcement on the performance of hot-rolled steel channels in the three proposed beam series, a 200 cm long reinforcement on the underside of the channel's lower flange (BMD) proved to be the most advantageous. This reinforcement (analyzing the results at a load of 40 kN) allowed for a 3.6% reduction in strain compared to the reference beams, a reduction in vertical displacement by approximately 1.1% at both measurement points, and a reduction in horizontal displacement by over 22%;
- for the BMK and BMZ beam series, there was no increase in ultimate force, and the effect of the reinforcement on deformation reduction compared to the reference beams was negligible. Furthermore, a reduction in horizontal displacement by approximately 9% (at a load of 40 kN) was observed.

The research results presented in this article should be considered illustrative due to the small number of beams analyzed and the scatter between the displacement and deformation results obtained for individual beams. At the same time, the results presented in this paper and in [23] indicate the limited effectiveness of using carbon fiber fabric reinforcements in hot-rolled elements subjected to bending and compression (this conclusion applies only to hot-rolled elements with the same cross-sectional shape and slenderness to lateral-torsional buckling value - in this case 0.903). Given the high strength of the reinforcing materials and the low strengthening effect, alternative methods for strengthening hot-rolled steel elements should be explored.

Acknowledgements

The research was financed by the Lublin University of Technology FD-20/IL-4/054.

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