Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal, 2025, 19(8), 141–147
https://doi.org/10.12913/22998624/204181
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Received: 2025.04.02
Accepted: 2025.06.15
Published: 2025.07.01

Influence of glued steel and composite tapes on the behaviour of axially compressed hot-rolled steel angles

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ABSTRACT

Hot-rolled steel angles are a profile commonly used as lattice bars in older types of roof girders. With the growing popularity of photovoltaic installations mounted on the roofs of steel halls, steel structure designers often face the problem of exceeding the load-bearing capacity of compressed lattice bars. This is particularly the case in old halls designed according to Polish standards. It was common practice to use reinforcements of steel structures by adding additional bars or flat bars using welding. Unfortunately, in some active industrial facilities, due to fire safety conditions, this is not possible. Therefore, this paper presents laboratory tests of axially compressed hot-rolled angles reinforced with the technique of gluing steel tapes, composite tapes and composite mats. The study involved 11 hot-rolled steel angles measuring 50 × 50 × 4 mm and 1 m long, made of S235 steel. Two angles were tested without reinforcement and were treated as reference samples. The remaining angles were reinforced with steel tapes and carbon fibre composite tapes bonded with epoxy glue or 3M VHB GPH-160GF tape. The last profile was reinforced with a carbon fibre mat. During the axial compression test, strains were measured using electro-resistance strain gauges and displacements at selected points were measured using the Aramis optical system. The results obtained showed a very beneficial effect of using bonded composite and steel tapes on limiting displacements and strains of the tested elements.

Keywords: hot-rolled steel profiles, reinforcement, steel tapes, CFRP.

INTRODUCTION

Relatively often, during the use of a steel structure, it is necessary to reinforce it. This may be the result of damage to the steel structure, but also the occurrence of additional loads. A popular method of reinforcing steel structures is the use of steel flat bars or plates, which are connected to the structure by welding or by using mechanical connectors [1]. However, welding is not always an acceptable solution (for example, due to fire regulations applicable to a given facility). In addition, the welding technique has its disadvantages, such as residual stresses caused by welding, which can lead to new damage in the existing structure [2, 3]. An alternative solution may be the use of bonded composite materials. Scientific publications often include analyses of the effectiveness of reinforcement using bonded CFRP (Carbon Fiber Reinforced Polymer) tapes in relation to reinforced concrete structures [4], masonry [5] or even wooden structures [6]. The constant lack of clear normative guidelines for the design of reinforcements of steel structures requires conducting numerous laboratory tests, which is pointed out in relation to steel telecommunications structures by [7]. The very favorable strength-to-weight ratio of CFRP composite materials and their corrosion resistance make them increasingly popular for modernization of steel elements [8]. Published research results show that making reinforcements using CFRP materials can effectively increase the bending strength [9] or compression strength [10] of both hot-rolled and thin-walled steel elements [11, 12]. Numerous examples of the use of adhesive joints in steel and aluminum structures have been described in [13]. However, a review of the literature did not find any studies comparing the effectiveness of reinforcement obtained after the use of adhesive steel tapes and composite tapes. Due to the high cost of CFRP materials, this issue seems to be interesting from an economic point of view and has become the subject of the research described in this publication. The research presented in the article, due to the limited number of samples, should be considered pilot studies, which are an introduction to broader laboratory studies. The presented research results indicate a certain trend regarding the effect of using specific types of reinforcement, but do not allow for the formulation of unambiguous final conclusions.

PREPARATION FOR TESTING

The test in the axial compression scheme was performed on 12 samples of 1 m length made of a 50 × 50 × 4 angle made of S235 steel. The first 3 samples were reference samples, named K1R, K2R, K3R. All other samples were reinforced by gluing steel tapes with a cross-section of 50 × 2 mm, CFRP tapes Sika CarboDur S512 or carbon fibre mats SikaWrap 230 C with a length of 0.9 m to the outer surfaces of the angle arms, so that both ends of the samples remained without reinforcement over a length of 5 cm.

Before starting the reinforcement, all samples were cleaned and matted using sandpaper and degreased using extraction naphtha.

In order to better illustrate the method of strengthening individual samples, Figure 1a was made. Detailed strength parameters of materials such as Sikadur-30 and Sikadur-330 adhesives, SikaWrap 230C mat or VHB GPH-160GF tape are available in the product catalog cards on the manufacturers' websites. The basic strength parameters of the Sika CarboDur S512 tape determined on the basis of our own research are Poisson's ratio v = 0.308 and Young's modulus E = 165 GPa. In the case of a steel tape made of S235 steel, the basic parameters are Poisson's ratio v = 0.3, Young's modulus E = 210 GPa and the yield strength of steel 235 MPa. Laboratory tests were started after at least 7 days from the reinforcement, in order to obtain full strength parameters of the Sikadur-30 and Sikadur-330 adhesives (according to the information in the product data sheets). The next step was to stick the electro-resistance strain gauge on the inner surface of the angle shelf (at a distance of 5 mm from the outer edge), in the middle of its span in order to measure deformations. Additionally, in the middle of the span of each sample, on the inner side of the cross-section, measuring points were glued, where displacements were measured. Figure 1b shows the location of the P1 measuring point, described in this paper, and the T1 electro-fusion strain gauge.

LABORATORY TESTS

The tests in the axial compression scheme were carried out in a Zwick&Roel testing machine (ZwickRoell GmbH & Co. KG, Ulm, Germany). The load was generated by moving the press piston at a rate of 2 mm/min, recording the load increase every 0.01 s. The samples were placed in specially prepared holders. Holes corresponding to the cross-section of the tested angles were cut in a 10 mm thick steel sheet. The samples were placed in the cut hole and subjected to load in the testing machine. During the test, strains were measured using TENMEX TFs-10 120Ω ± 0.2% electro-fusion strain gauges and displacements at the control point were measured using the Aramis

Table 1. Nomenclature and method of strengthening the tested samples

Determination of tested samples	Series designation in the analysis of results	Method of reinforcement
K1R, K2R, K3R	KR	Reference samples - no reinforcement
K1SK, K2SK	KSK	Reinforcement with steel tape made of S235 steel with a cross-section of 2 mm x 50 mm, tape glued with SikaDur-30 adhesive, layer thickness 0.9 mm
K1ST, K2ST	KST	Reinforcement with S235 steel tape with a cross-section of 2 mm x 50 mm, tape glued to 3M VHB GPH-160GF tape with a width of 50 mm and a thickness of 1.6mm
K1M	KM	Reinforcement of SikaWrap 230 C carbon mat with SikaDur 330 adhesive
K1CK, K2CK	KCK	Reinforcement with CFRP tape Sika CarboDur S512, tape glued with SikaDur-30, layer thickness 1.3 mm
K1CT, K2CT	KCT	Reinforcement with CFRP tape Sika CarboDur S512, tape bonded to 3M VHB GPH-160GF tape, 50 mm wide, 1.6 mm thick

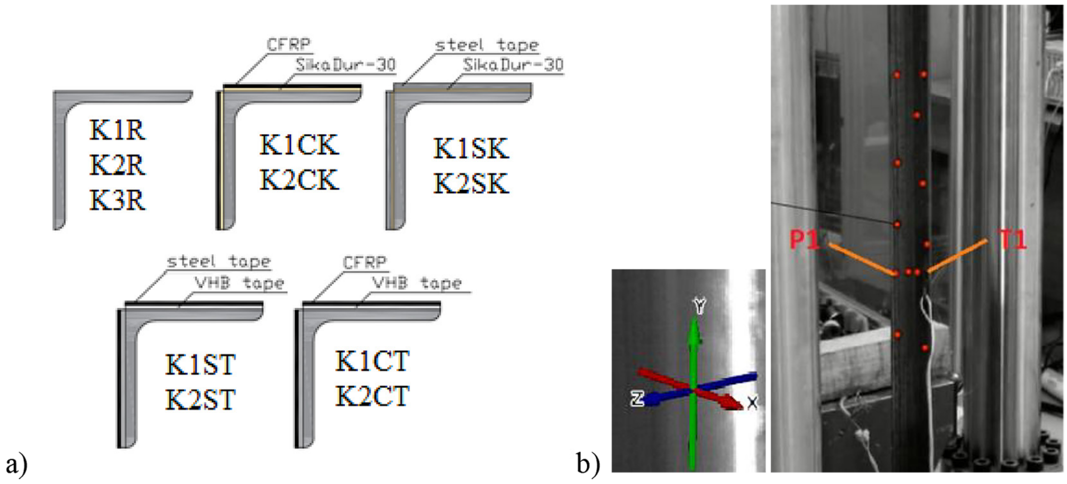

Figure 1. (a) The designation of the groups of tested samples and the method of strengthening, (b) measurement points

system. The use of the Aramis system allowed for the measurement of sample displacements in 3D. Photos of the test stand are shown in Figure 2.

All samples were characterized by the same form of destruction. During the laboratory tests, the load was applied to the samples continuously until failure (not in load-unload cycles). Under the influence of the applied load, the arms of the angles first spread apart and the entire angle moved from its equilibrium position towards the top, which can be seen in the photo of the samples after destruction (Figure 3a). During laboratory tests, a partial separation of the CFRP tape was observed in the sample marked K1CK at a load of about 81 kN. For this reason, in the further part of the work it was decided to analyze the values of displacements and strains for the load level of 80 kN. In the remaining samples, in which both steel and CFRP tapes were glued with glue, the destruction of the tapes or the joint was observed only after exceeding the value of the destructive force (Figure 3b). In the case of reinforcements

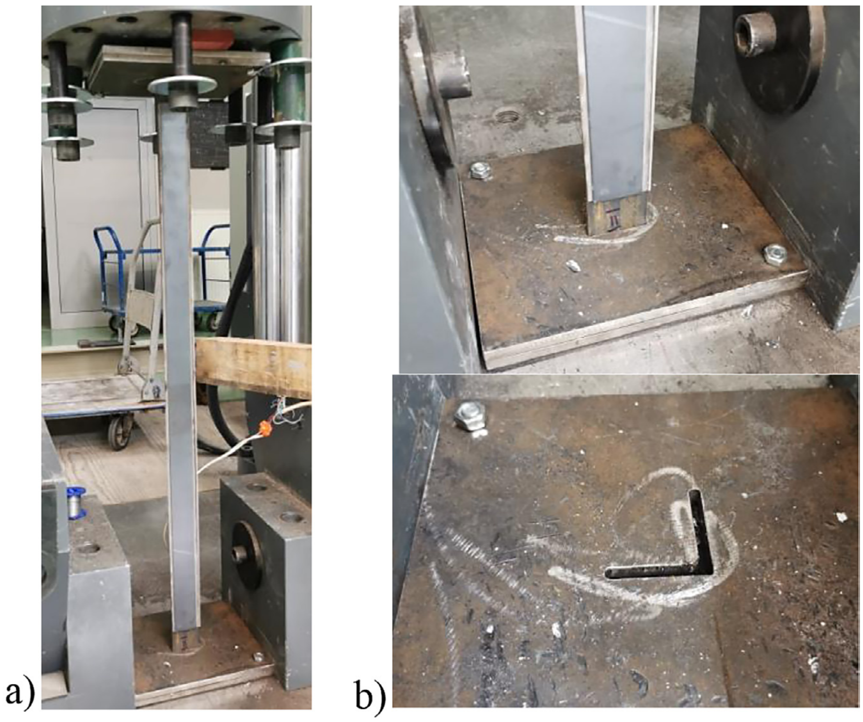

Figure 2. Photograph of (a) the test stand, (b) detail of the method of mounting the sample

made using VHB tape, gradual stretching of the tape was observed, which was caused by the deformation of the sample and the high stiffness of the reinforcing tape (Figure 3c).

LABORATORY TEST RESULTS

During the test, displacements in the middle of the angle span at point P1 and strains were measured in all samples using an electro-fusion strain gauges T1. The samples were tested to destruction. Each time, the use of any form of reinforcement contributed to an increase in the value of the destructive force (even in the case of K1CT, in which the CFRP tape partially detached during the test). The values of the destructive force obtained by individual samples are presented in Table 2. The table does not contain data obtained by sample K3R due to the press being switched off at a load below 90 kN.

All reinforcement methods increased the value of the destructive force. Referring to the average values calculated for each series, the greatest increase in force compared to the reference samples was achieved with the use of reinforcement with steel tapes (by 38.2%) and CFRP (by 28.3%) bonded with SikaDur-30 adhesive. Reinforcement using tapes bonded with VHB tape contributed to an increase in the value of the destructive force by 16.5% in the case of steel tapes and by 12.2% when using CFRP tape. The least effective was the reinforcement using CFRP mat, causing an increase in the value of the destructive force by 4.3% compared to the reference samples. The results of the strain measurement at the place of attachment of the strain gauge T1 are presented in the graph (Figure 4). The results of displacements at point P1 relative to the Z axis are presented in Figure 5. Due to the large number of samples and low transparency of the presented results, Table 3 was developed, which presents the results of displacements and strains at a load level of 80 kN.

Considering the effect of reinforcement on reducing the strain values compared to reference samples at a load of 80 kN, it can be stated that the most beneficial is the use of reinforcements using steel tapes glued with SikaDur-30 (reduction of strain values by 24.7%) and VHB tape (by 12.4%). Reinforcement using CFRP tapes connected with SikaDur-30 glue allowed for reducing the strain values by 10.3%, connected with VHB tape by 6.7%, while the use of CFRP mats caused a decrease in the strain values by 4.4% compared to reference samples.

Table 2. Values of the destructive forces obtained by individual samples and average values for a given group

Sample symbol	Destructive force [N]	Average value of the destructive force in a given group [N]
K1R	92375	91024
K2R	89673	
K1CK	115340	116768
K2CK	118196	
K1CT	99383	102173.5
K2CT	104964	
K1M	94895	94895
K1SK	131772	125764.5
K2SK	119757	
K1ST	106109	106054
K2ST	105999	


a) b) c)

Figure 3. Photos of example forms of destruction of the tested samples, (a) method of sample destruction, (b) delamination of the CFRP tape, (c) damage to the VHB tape

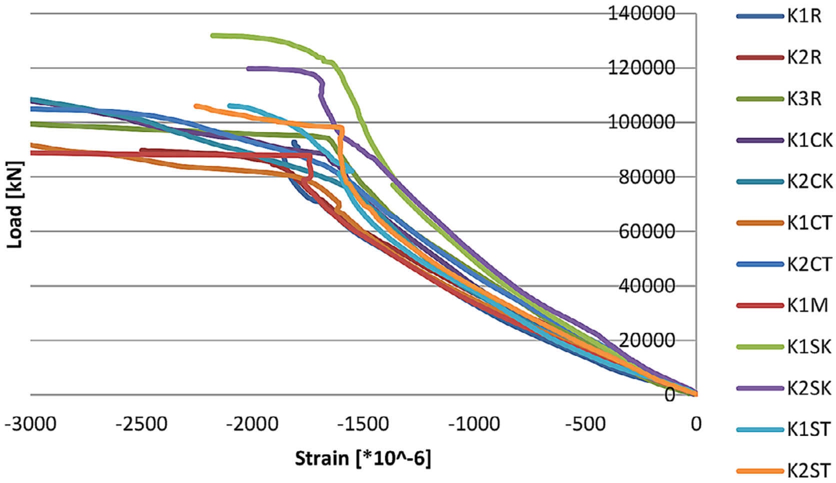

Figure 4. The load – strain relationship graph for the tested samples

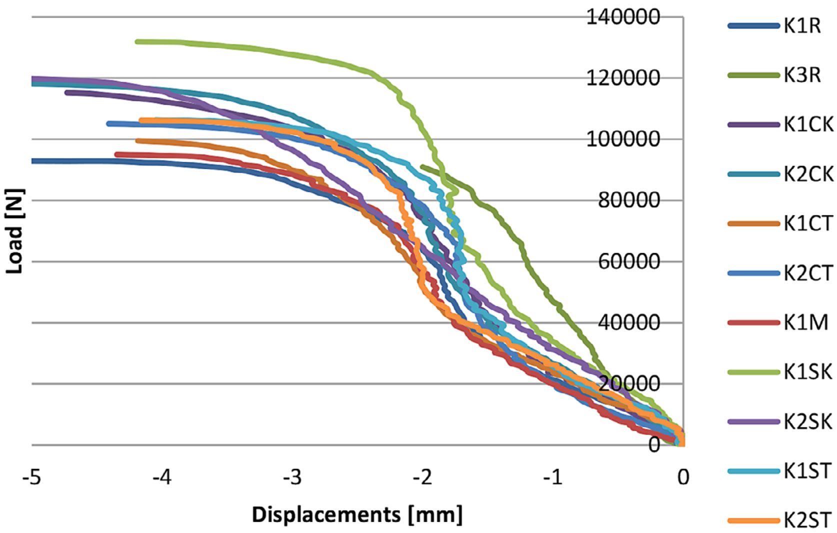

Figure 5. Load – displacement relationship graph relative to the z axis for the tested samples

Table 3. Displacement and strain values of individual samples at a load level of 80 kN

Samples	Strain (·10⁻⁶)	Displacements (mm)			Strain (·10⁻⁶)	Displacements (mm)		
		dx	dy	dz		dx	dy	dz
K1R	-1828	-7.13	-1.65	-2.65	-1819	-6.39	-1.69	-2.27
K2R	-1809	X	X	X				
K3R	X	-5.64	-1.73	-1.88				
K1CK	-1577	-4.80	-1.67	-2.08	-1631	-4.89	-1.76	-2.08
K2CK	-1685	-4.97	-1.84	-2.07				
K1CT	-1800	-6.09	-1.79	-2.38	-1696	-5.75	-1.73	-2.23
K2CT	-1592	-5.41	-1.67	-2.07				
K1M	-1738	-6.68	-2.06	-2.54	-1738	-6.68	-2.06	-2.54
K1SK	-1366	-4.20	-1.61	-1.78	-1369	-4.27	-1.52	-2.12
K2SK	-1371	-4.33	-1.42	-2.46				
K1ST	-1601	-5.39	-1.58	-1.86	-1593	-5.70	-1.70	-2.02
K2ST	-1584	-6.01	-1.81	-2.17				

Analyzing the results of sample displacements obtained during laboratory tests, it was found that the use of a carbon fiber mat did not limit the displacements compared to the results obtained by reference samples. The most effective was again the reinforcement using steel tapes glued to a steel profile, reducing the displacements compared to reference samples by up to 33.2% (relative to the *x* axis). Moreover, only this method of reinforcement reduces the displacements relative to the *y* axis. Reinforcement using CFRP tapes glued together allows for limiting the displacements relative to the x axis by 23.5%. The use of reinforcements using steel tapes and CFRP tapes connected to an angle with a VHB tape allows for limiting the displacements to a similar extent (by about 10% relative to the x axis) with a slight advantage of steel tapes.

CONCLUSIONS

The laboratory tests presented in this paper allow for the following conclusions to be drawn:

1. Each of the five proposed reinforcement methods allowed for an increase in the value of the destructive force.
2. The least effective was the reinforcement using the SikaWrap 230V mat glued along the arms of the angle. Its use resulted in a reduction of strains by only 4.4% compared to the reference samples and did not contribute to the reduction of displacements of the tested sample.
3. The best results were obtained using reinforcement made of steel tapes glued to the angle using sikadur-30 adhesive. In relation to reference samples, this reinforcement method allowed for an increase in the value of the destructive force by 38.2%. A reduction in strains at the place where the t1 strain gauges was glued by 24.7% and displacements by up to 33.2% (relative to the x axis).
4. Reinforcement made using cfrp tapes glued to the angle with sikadur-30 in relation to reference samples enabled an increase in the value of the destructive force by 28.3%. A reduction in strains at the place of gluing the t1 strain gauges by 10.3% and displacements by up to 23.5% (relative to the x axis). Such a difference between the effects of reinforcement using steel tapes and cfrp tapes in relation to the costs of composite tapes discourages their use in hot-rolled steel elements.
5. The effects of reinforcement using steel tapes connected with VHB tape are surprising. Although the tape delaminates with large sample deformations, this method allows for an increase in the value of the destructive force by over 16% and a reduction in strains and displacements by over 10%, the effects obtained with reinforcement with CFRP tapes were slightly lower.

The described laboratory tests are pilot studies and the obtained test results should be treated as illustrative due to the small number of samples.

Acknowledgements

The grant was financed in the framework of the pro-quality program of Lublin University of Technology “Grants for grants” (Grant nr: 7/GnG/2023).

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