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Influence of Uplift Load on Torsional Restraint Provided to Steel Thin-Walled Purlins by Sandwich Panels

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Abstract

The sandwich panels have been widely used as members of roof and wall cladding. In addition to their primary function, they can provide lateral and torsional restraints to the supporting members and therefore contribute to their buckling resistance. The availability of the provided restraints is influenced by the direction of the load applied to the surfaces of the panels. For the uplift load, no torsional restraint is conservatively considered due to reduction of the contact area between the panels and the supporting metal members. Possible small rate of the torsional restraint should be verified by experimental investigation.

The paper focuses on the experimental verification of the torsional restraint provided to steel purlins of thin-walled cold-formed cross-sections by adjacent sandwich panels. For the first series of tests a simple test set-up with no external load applied to the surface of the panel was utilized. The second series comprises tests of the torsional restraint provided to steel purlins by sandwich panels under uplift load. A complex test set-up taking into account the external load applied to the surfaces of the panels was used. The results of both test approaches are compared and the influence of the uplift load on the torsional restraint for the tested specimens is evaluated.

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Keywords: Buckling; experiment; purlin; sandwich panel; stabilization; thin-walled beam; torsional restraint

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1. Introduction

Planar members of roof and wall cladding (e.g. sandwich panels) are in most cases supported by metal members of thin-walled cross-sections (purlins, girts). Due to connection of cladding, a metal member can be fully or partially

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restrained against lateral displacement and rotation. The prevention of the deformation of the metal member contributes to its buckling resistance [1,2]. Correct consideration of the restraint along its span can positively influence the efficiency of the structural design. The adjacent members of cladding can provide lateral restraint (effected by certain shear stiffness given by the planar member) and torsional restraint (effected by certain rotational stiffness) for the thin-walled member [3,4]. The lateral restraint provided by the planar members of cladding to both hot-rolled and cold-formed members can be utilized for downward as well as uplift load applied to the surfaces of the sandwich panels. The torsional restraint can standardly be considered in case of the downward load only [5]. Due to the uplift load applied to the surfaces of the panels, the reduction of the contact area between the panels and the metal members between the fasteners occurs which can result in rotation of the metal member between the fasteners or along its length and decrease in the rotational stiffness [5]. For this reason, the zero rotational stiffness is conservatively considered for the uplift load on the sandwich panels. According to [6], certain values of the rotational stiffness might be available when metal members of thin-walled cold-formed cross-sections are utilized. Due to lack of data regarding the torsional restraint provided to thin-walled members by sandwich panels under uplift load, experimental research in this field is necessary and the values of the rotational stiffness should be provided by testing. The standard [7] gives a simple test set-up for experimental verification of the torsional restraint provided to thin-walled beams by planar members. As it does not take into account the external load applied to the surfaces of the planar members, it is not suitable to investigate the effect of the uplift load on the torsional restraint. Moreover, it is assumed, due to the absence of external load, that the test set-up according to the standard [7] gives overestimated values of the rotational stiffness [6]. The document [6] provides a more complex test set-up with external load applied to the surfaces of the panels.

The paper presents results of two series of tests performed at the Testing Laboratory of the Institute of Metal and Timber Structures, Faculty of Civil Engineering, Brno University of Technology. The first series contains the tests according to the standard [7] (with no uplift load). The second series comprises tests of the torsional restraint provided to steel thin-walled purlins by sandwich panels under uplift load with the use of the principle of the test set-up according to [6]. The test results obtained using both approaches are compared and discussed.

Nomenclature

C_D	rotational stiffness
E	modulus of elasticity
F	point load applied at midspan of the flange of the purlin
F_T	force on lever arm causing the rotation of the purlin
K	total combined lateral spring stiffness
K_A	lateral spring stiffness corresponding to the rotational stiffness of the connection
K_B	lateral spring stiffness due to distortion of the cross-section of the purlin
K_C	lateral spring stiffness due to the flexural stiffness of the planar members
K_{adj}	adjusted value of the total lateral spring stiffness
K_{obs}	total lateral spring stiffness obtained from a test
R	lever arm
a	distance of a fastener and the web of the purlin
b	width of the flange of the purlin
h	depth of the purlin
h_δ	distance of the point of the lateral displacement measurement from the bottom flange of the purlin
l_A	width of a planar member adjacent to the purlin
l_B	length of the purlin
p	uniformly distributed areal load
t	thickness of the purlin
δ	measured displacement of the purlin
μ_R	ratio between actual and nominal thickness of the purlin
ν	Poisson's ratio

2. Definition of the torsional restraint

The torsional restraint is characterized by certain value of the rotational stiffness. It is defined as torsional moment causing the unit rotation of the flange of the restrained member. It is influenced by the stiffness of the connection of the adjacent planar members and the thin-walled member, flexural stiffness of the planar members and by the stiffness corresponding to the distortion of the cross-section of the thin-walled member [7,8]. It is also affected by the direction of the external load applied to the planar members [9].

3. Specimens

For both series of the tests of the torsional restraint given to steel thin-walled purlins by sandwich panels the specimens of the identical material were used. The steel zinc-coated purlins of thin-walled cold-formed Z-sections were fastened to the sandwich panels using self-drilling screws (four screws per one sandwich panel and one purlin). The depth h of the cross-sections of the purlins was 150 mm, the thickness t was 3 mm, the width of the flange b was 48 mm. As planar members stabilized by the purlins, sandwich panels with thin steel slightly profiled facings (thickness 0.5 mm) and polyurethane insulating core of the thickness of 40 mm were utilized. The width of one panel was 1 m, the self-weight 8.6 kg/m^2. In Fig. 1, the cross-sections of the purlins and the sandwich panels and a scheme of the fastening are displayed.

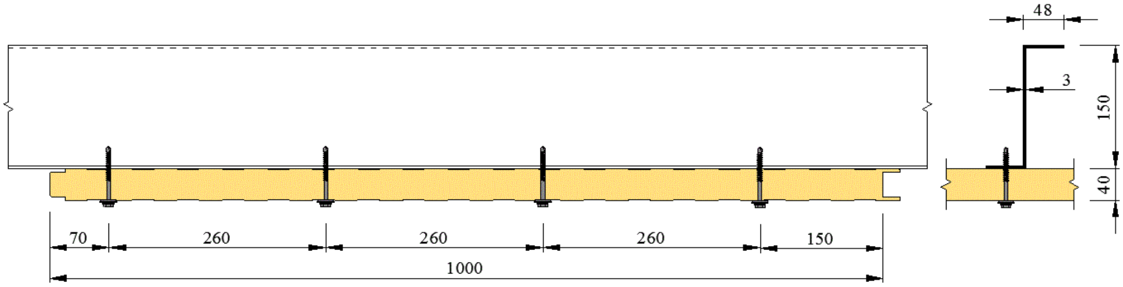

Fig. 1. Cross-sections of the purlins and sandwich panels and scheme of the fastening.

4. Experimental verification of the torsional restraint according to the standard procedure

The actual standard for design of steel structures [7] provides a simple test set-up for verification of the torsional restraint given to thin-walled members by planar members and sheeting. A thin-walled member of a depth of h is fixed to a planar member and loaded by a point load F at midspan of the free flange. This force should induce lateral displacement of the free flange δ of a magnitude of h / 10. Knowing the displacement of the free flange δ and the force F, it is possible to calculate the total combined lateral linear spring stiffness K using (1). The combined lateral spring stiffness K, in general, comprises the components K_A, K_B and K_C and can be determined using (2). As the value of K_C is large in comparison with other components, the fraction 1 / K_C can be neglected [7]. It results in (3).

$$\frac{1}{K}=\frac{\delta}{F} \quad (1)$$

$$\frac{1}{K}=\frac{1}{K_A}+\frac{1}{K_B}+\frac{1}{K_C} \quad (2)$$

$$\frac{1}{K}=\frac{1}{K_A}+\frac{1}{K_B}=\frac{\delta}{F} \quad (3)$$

The component K_B expresses the distortion of the metal thin-walled cross-section and depends on the geometry and material characteristics of the member. The standard [7] gives a formula for its calculation in case the displacement is measured at the same position (along the depth of the cross-section) as the point of application of the force. For the purposes of the test evaluation, a general formula (4) was derived using the method of the virtual work for the case of an arbitrary position of the measurement of the lateral displacement (measurement in a distance of h_δ from the bottom flange).

$$K_B = \frac{E \cdot t^3 \cdot l_B}{4 \cdot \left(1-\nu^2\right) \cdot \left[\frac{h_\delta^2}{2} \cdot \left(3 \cdot h - h_\delta\right) + b_{mod} \cdot h \cdot h_\delta\right]} \tag{4}$$

The component K_A can be determined using K (result of a test) and K_B. Then the rotational stiffness C_D, which characterizes the torsional restraint, is taken as (5). In (4), the value b_{mod} is taken as a if the load causes the contact of the purlin and the planar member at the purlin web or $2 \cdot a + b$ if the load causes the contact of the members at the tip of the purlin flange.

$$C_D = \frac{K_A \cdot h \cdot h_\delta}{l_A} \tag{5}$$

Three tests (E1, E2, E3) of the torsional restraint provided to thin-walled purlins by sandwich panels using the standard test set-up were performed. Pictures of the test set-up are in Fig. 2. The specimen consisted of a purlin of a length of 1 m and a piece of the sandwich panel and was fixed to a steel frame (with stiffening construction). The force F was applied using a bridge crane and its magnitude was measured using a force transducer. The purlin was equipped with sensors of displacement at midspan and at its left and right ends. Three cycles of loading of the purlin were performed in the frame of each test.

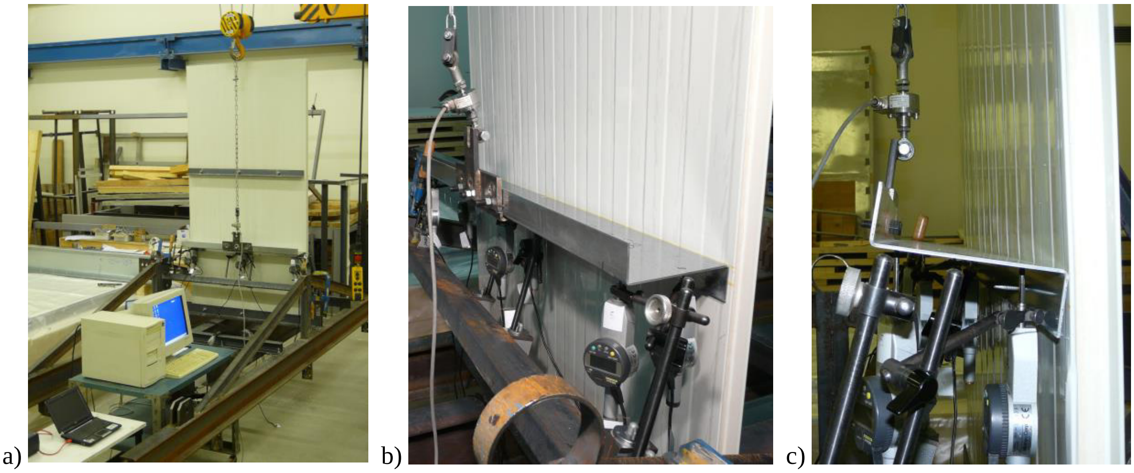

Fig. 2. (a) Test set-up; (b) detail; (c) deformation of the purlin.

Using the force F and the displacement at midspan δ, the total combined lateral spring stiffness K_{obs} was obtained as the slope of the line approximating the force-deformation curve. The adjustment of the test results (with respect to actual thickness of the purlin) was performed using a procedure given in [7] with the use of the ratio between actual and nominal thickness of the purlin μ_R. The adjusted value K_{adj} and the value of K_B were utilized to calculate the component K_A and, subsequently, the value of the rotational stiffness C_D using (5). The relationships between the force F and the displacement δ (measured in the distance of h_δ from the bottom flange) for the performed tests are in Fig. 3. The calculation of the rotational stiffness is summarized in Table 1.

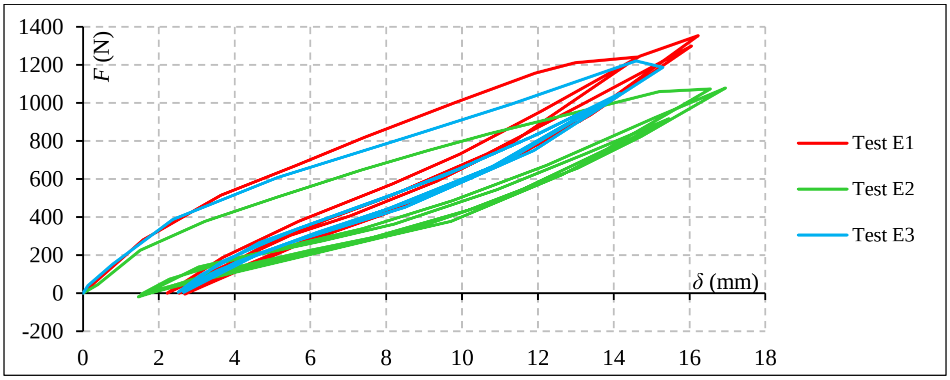

Fig. 3. Relationships between the force and the displacement.

Table 1. Results of tests E1, E2 and E3 and calculation of the rotational stiffness

	μ_R	h_δ (mm)	$b_{mod} = a$ (mm)	K_{obs} (N/mm)	K_{adj} (N/mm)	K_B (N/mm)	K_A (N/mm)	C_D (Nmm/mm/rad)
Test E1	0.96	90.00	24.75	86.83	90.51	869.19	101.03	1363.91
Test E2	0.96	92.00	20.25	62.70	65.07	868.03	70.34	970.67
Test E3	0.97	89.00	21.50	77.71	80.25	907.34	88.03	1175.26

5. Experimental verification of the torsional restraint under uplift load

Document [6] provides a test set-up for experimental verification of the torsional restraint provided by sandwich panels to thin-walled members which takes into account the effect of the external load p applied to the surfaces of the panels. Its scheme is in Fig. 4. The specimen consists of two sandwich panels and two purlins fastened to the panels. At the ends of one purlin, lever arms should be attached to apply the torsional moment. The lever arms should be connected at their ends by a transversal member. The displacements of the purlin and applied force (resulting in the torsional moment) should be measured.

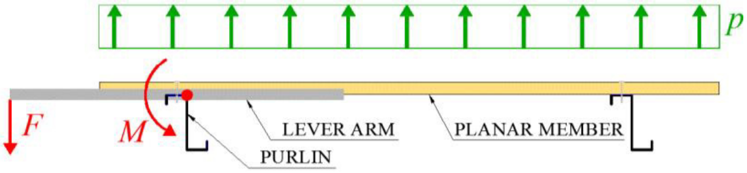

Fig. 4. Scheme of the test set-up.

The tests of this series were a subject of the paper [10]. For the purposes of clarity, they will be described briefly. The test set-up used for the second series of tests is based on [6]. For the application of the uniformly distributed load on the surfaces of the panels, the vacuum test method was used [11,12]. The suction in a timber vacuum chamber (caused by vacuum pump) simulated the uplift load applied to the panels. The tightness of the vacuum chamber was ensured by a foil. The magnitude of the load was continuously measured using a digital manometer. The specimen was placed on a steel frame with stiffening construction. Sandwich panels of the length of 4 m were used. At the ends of one purlin, steel lever arms were attached and connected at their ends by a steel transversal girder. The bridge crane in the laboratory was connected with the transversal girder at its midspan. By operating of the bridge crane, the force F_T on the lever arm R was induced and continuously measured using a force transducer. The displacements of the purlin caused by the resulting torsional moment were measured using sensors of displacement. The loading of the purlin by the torsional moment was performed under no uplift load and under five different levels of the uplift load caused by the vacuum test method. In the frame of each level of the load, three cycles of loading by the torsional moment (rotation of the purlin) were executed. Pictures of the test set-up are in Fig. 5. Two tests (T1, T2) were performed.

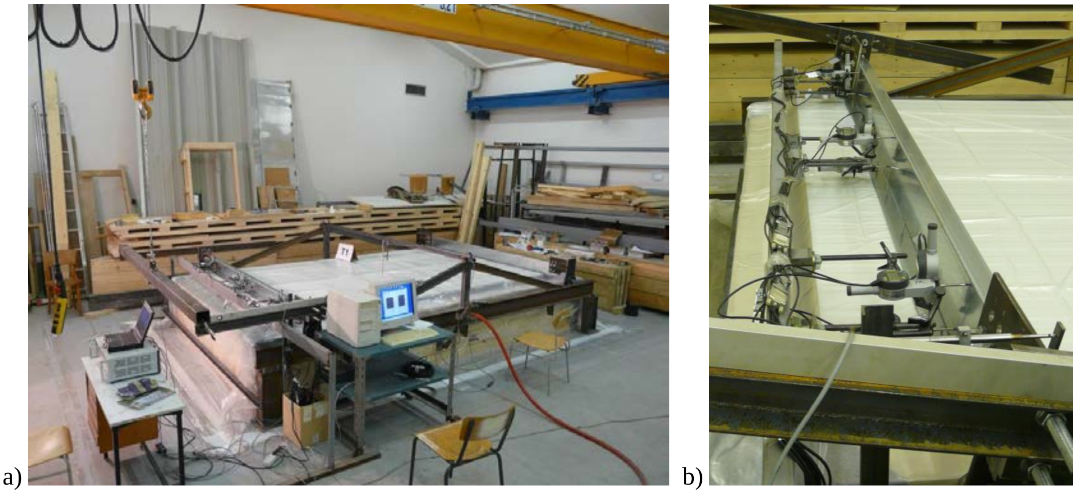

Fig. 5. (a) Test set-up; (b) deformation of the purlin.

As the force was not applied directly to the top flange of the purlin, the appropriate value of the force F required for the calculation of the total lateral spring stiffness was derived using a mechanical model. The calculation resulted in (6).

$$F = 1.125 \cdot \frac{F_T \cdot R}{h} \tag{6}$$

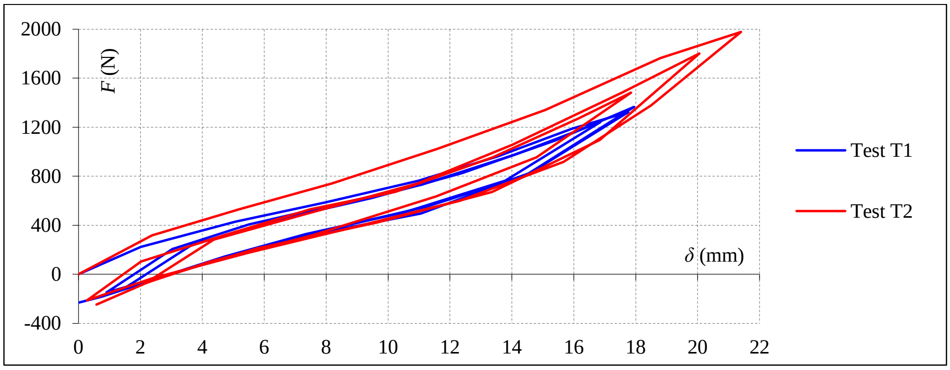

Fig. 6. Relationship between the force and the displacement (last level of the uplift load).

The force F and the displacement at midspan δ were used for calculation of the total lateral spring stiffness obtained from a test K_{obs} for each level of the uplift load as the slope of the line approximating the force-deformation curve. The adjustment of the test results was performed according to [7] using the ratio between actual and nominal thickness of the purlin μ_R. Using the adjusted value K_{adj} and the value of K_B, the component K_A was calculated and used for the calculation of the rotational stiffness C_D.

The typical relationship between the force F and the deformation δ (measured in the distance of h_δ from the bottom flange of the purlin) is in Fig. 6 (last level of the uplift load). The relationships for other levels were similar as the one shown. The results for all levels of the uplift load for both tests (T1, T2) are summarized in Table 2. Details can be found in [10].

Table 2. Results of tests T1 and T2.

 p (N/m^2)	Test T1 K_{adj} (N/mm)	Test T1 K_B (N/mm)	Test T1 K_A (N/mm)	Test T1 C_D (Nmm/mm/rad)	Test T2 K_{adj} (N/mm)	Test T2 K_B (N/mm)	Test T2 K_A (N/mm)	Test T2 C_D (Nmm/mm/rad)
0	102.82	1244.13	112.09	1067.61	118.00	1199.79	130.87	1275.98
160	108.71		119.12	1134.66	123.66		137.87	1344.20
320	102.72		111.97	1066.47	119.59		132.83	1295.11
480	94.01		101.69	968.59	116.68		129.25	1260.16
640	85.81		92.17	877.93	112.26		123.84	1207.48
800	80.21		85.74	816.63	93.84		101.81	992.63

6. Comparison of results

The results of both test methods (with and without the uplift load) in form of the resulting rotational stiffness are graphically presented in Fig. 7 depending on the level of the uplift load. Dashed lines present the rotational stiffness obtained from standard tests according to [7] (with no uplift load).

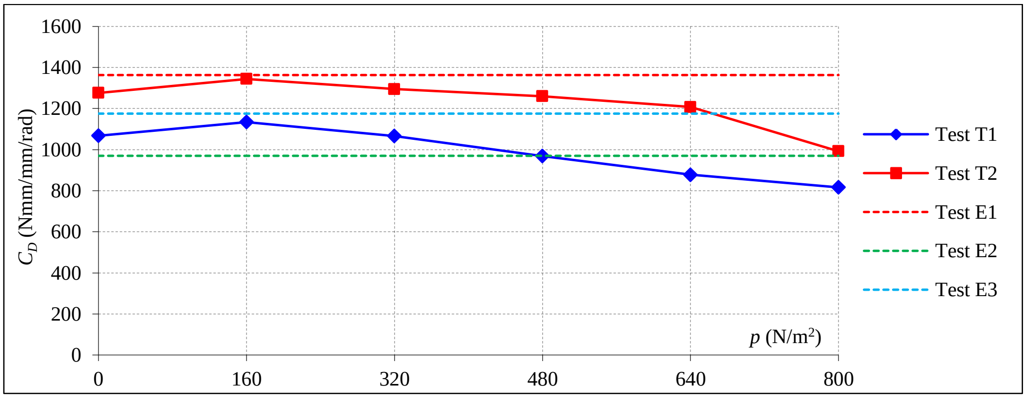

Fig. 7. Comparison of results.

7. Results and discussion

The torsional restraint provided to steel thin-walled members by sandwich panels under uplift load is standardly not considered in the frame of structural design. The performed tests indicate that practically significant values of the rotational stiffness might be available for thin-walled members stabilized by sandwich panels under uplift load. A slight decrease of the rotational stiffness with increasing magnitude of the uplift load was observed.

For the tested specimens, the tests also indicate fairly comparable values of the rotational stiffness obtained as results of different test methods. The simple standard test set-up gives similar values of the rotational stiffness as the complex test set-up taking into account the external uplift load applied to the surfaces of the sandwich panels.

8. Conclusions

The paper summarizes the results of two series of tests of the verification of the torsional restraint provided to thin-walled members by sandwich panels under uplift load. Two different test set-ups were utilized and results were compared. For the tested specimens, considerable rate of the torsional restraint was observed for both test methods. Both test approaches provided comparable values of the rotational stiffness. A more extensive and broader experimental research would bring another findings and generalization regarding the actual behavior of the thin-walled members stabilized by sandwich panels under uplift load. An inconvenience of testing is the complexity of the test set-up taking into account the uplift load applied to the surfaces of the panels.

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