Research Article

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Behaviour of steel sheeting connections with self-drilling screws under variable loading

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Abstract: Connections made by self-drilling screws are often used in steel cold-formed structures and sheeting. Their structural properties, such as resistance, flexibility and ductility are obtained by testing under monotonically increasing loading and can influence on overall behaviour of structures. This paper presents results of experimental study how variable load deteriorates those structural properties of lap shear connections with self-drilling screws. One monotonic and four variable loading histories were utilized, with displacement and force control. Applied loading histories were aimed to simulate persistent design situation, which referred to the conditions of normal use according to EN 1990. Deterioration of resistance and flexibility have been assessed for each variable loading history. It was observed that resistance deterioration is directly proportional to loading range. In case of flexibility, at small displacement range connectors become stiffer. Degradation of flexibility starts to increase at larger displacement range.

Keywords: self-drilling screws, lap connections, structural properties, variable loading, deterioration

1 Introduction

Steel corrugated sheets are often used as elements of roof or wall cladding and floor decking. In modern design it is possible to utilize their diaphragm action, where sheeting stiffness and strength in shear make a very positive contribution to the overall strength and stability of a whole structure or individual structural elements. Idea of such stressed skin design has started in the second half of last century [1]. According to the contemporary rules and stan-

dards [2, 3] the interaction between structural members and sheeting panels, that are designed to act together as parts of a combined structural system, may be allowed for.

Methods of stressed skin design, that utilize sheeting as an integral part of a structure, may be used only under the conditions that suitable structural connections are applied to transmit diaphragm forces between adjacent sheets and between ends of the sheets and supporting members of steel framework. Connections between thin sheets are usually made by blind rivets, self-tapping or self-drilling screws. They should not loose in service and keep mechanical properties as design resistance, flexibility and ductility during their working live. The shear design resistance and flexibility of mechanical fasteners used in steel sheeting are determined by set of tests according to [4].

Such tests are carried out under monotonically increasing loading, which correspond to static conditions. But real buildings, where stressed skin is predominantly used (mostly low-rise) are loaded in variable manner. Variable actions come from climate impacts, like snow, temperature, gusts of wind, etc. Under variable actions structural properties of connections can deteriorate in terms of strength and stiffness, so effect of this deterioration can influence the behaviour of sheeting panels and finally interaction between them and structural members.

The aim of this paper is to present results of experimental study in which series of lap shear connections with self-drilling screws were tested under monotonic and repeated loading. Conducted research is attempt to assess deterioration phenomena which occur in steel sheeting connections made with self-drilling screws. Applied loading histories were aimed to simulate persistent design situation, which referred to the conditions of normal use according to EN 1990 [5]. Seismic behaviour of such connection [6] is outside the range of this study, however some elements of methodology from such tests have been adopted in this research.

Although many publications present analyses and compares various aspects of such connections behaviour under monotonic loading, e.g. [7–9], rather very few publications e.g. [10, 11] can be found in the literature that dis-

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cuss their behaviour under variable load conditions. So further study of the issue is still required.

2 Experimental investigation of connections subjected to shear

2.1 Shear test specimen

A number of experimental shear tests have been conducted to determine several mechanical properties of self-drilling screws in steel sheeting under static and repeated loads. The test arrangement was taken from ECCS Publication [4], which recommends two fasteners in side lap connection in order to reduce the effects of distortion and curling. Three different sheet thicknesses were considered: 1 mm, 1.25 mm and 1.5 mm. Steel grade S355 was used. The material was sandblasted and left uncoated. HILTI self-drilling screws type S-MD 01 Z with diameter $d = 5,5$ mm were used for the whole range of the specimens connections. The fastener type was chosen in accordance with maximum drilling capacity of the sheets in each group of thickness. The connections dimensions and fastener placement were selected in reference to the fasteners diameter as featured in the ECCS recommendation [4]. The test specimen is shown in Figure 1, while the summary of the experimental study is given in Table 1. The self-drilling screws were assembled by an appropriate screwdriver in compliance with the manufacturers installation instructions. The geometry of the assembled specimens was measured before testing and confronted with the maximum tolerances [4].

Figure 1: Geometry of single specimen; 1-self drilling screw HILTI S-MD 01 Z 5,5x19; 2-grip area, 3-reference points for extensometer

Tests were conducted in INSTRON 1200 kN JD1 testing machine. The machine can be programmed to run monotonic or variable cyclic tension or compression tests controlled by loading or deformation rate. The displacement increment was measured by an optical extensometer. The extensometer gauge length was taken from ECCS publication [4] referring to the fastener diameter and test arrangement and is given in Table 1. The results obtained from the extensometer and the machine grip displacement showed satisfying agreement through the test progression.

The plan of the experiment comprises two groups of tests according to the applied load history: fastener under static and repeated loads.

Table 1: Dimension of test specimens

Group of specimens	Thickness of sheets, t [mm]	Width of sheets, w [mm]	Extensometer gauge length, L_0 [mm]	Fasteners spacing	
				e_1 [mm]	p_1 [mm]
S1	1.00	60	150	30	60
S2	1.25				
S3	1.50				

2.2 Monotonic loading of lap connections

Shear tests under monotonic loading were carried out to determine the characteristic resistance and flexibility of the fasteners depending on the sheet thickness. The number of specimens dedicated for static loading test amounts to 6, 8 and 6 for sheet thickness 1.0 mm, 1.25 mm and 1.5 mm, respectively. Monotonic loading (M) has monotonically increasing character, see Figure 2. The load application was controlled by an appropriate displacement rate, which did not exceed 1 mm/min. The specific value was selected to avoid the force accretion over 1 kN/min. The observed resistance of the connection was measured as a

Figure 2: Monotonic loading history.

maximum load recorded within 3 mm of the relative displacement. The tests were continued beyond the deformation value of 3 mm, up to maximum value equal to $e_{max} = 12 \div 15$ mm.

2.3 Variable loading of lap connections

In order to assess degradation phenomena which can occur under variable loading, a few of variable loading histories were applied. The patterns of these histories are presented in Figure 3a-d.

First one (V1, see Figure 3a) has pattern according to ECCS recommendations [12]. The history contains few cycles in elastic range, which are followed by groups of three cycles whose amplitude increases, with unloading to zero value and with displacement control. As a level of reference, value of displacement e_k corresponding to characteristic resistance of one screw was accepted. Reference displacement e_k was obtained during monotonic loading in every tested group of specimens (S1÷S3). Procedure for its prediction is described in next chapter.

Next considered loading histories have repeated character, with groups of three cycles whose amplitude increases, with unloading to certain level (not equal to zero), Figure 3b, 3c. In case of V2 history (Figure 3b) loading was controlled by displacement and level of unloading was equal to $0.5e_k$. In case of V3 history (Figure 3c) loading was controlled by force and level of unloading was equal to $0.5R_k$, where R_k is characteristic resistance of considered group of specimens. These loading scenarios were supposed to simulate typical loading histories, where maximum value of loading comes from sum of permanent and variable actions.

The last loading history V4 (Figure 3d) simulates overloading of the joint in third cycle beyond elastic range and afterwards repeated loading with smaller amplitude.

Figure 3: Variable loading histories; a) cyclic according to ECCS; b) repeated with displacement control, c) repeated with force control, d) repeated with overload in third cycle.

3 Test results

3.1 Structural properties of connections obtained from monotonic loading

Load-deformation response of one group of specimens obtained under monotonic loading is presented in Figure 4. The force values refer to one connector (one-half loading of the connection).

The characteristic resistance R_k of the fastener as a single screw assembled in a sheet was calculated from the sta-

tistical evaluation of monotonic shear tests results, according to the ECCS publication [4].

$$R_k = R_m - k \cdot s \quad (1)$$

where R_m is mean value of test results obtained from a minimum of five tests, k is coefficient which depends on the number of test observations and chosen confidence level [5] and s is standard deviation. The calculations were done

Figure 4: Monotonic load-deformation response of the S2 group (with 1,25 mm thick steel sheets).

Table 2: Structural properties of self-drilling screws from statistical evaluation of test results.

Group	Characteristic resistance, R_k [kN]	Displacement corresponding to R_k , e_k [mm]	Ductility, e_u [mm]	Number of specimens [-]
S1	2.9	0.6	7.1	6
S2	4.1	1.0	6.5	8
S3	5.2	1.3	8.3	6

Figure 5: Method of prediction e_k (displacement corresponding to the characteristic value of resistance R_k) and e_u (ductility of connections).

in 3 groups of sheet thicknesses separately and results are presented in Table 2. The values of R_k show correct trend of increasing resistance along with the material thickness.

Additional mechanical properties of the joints predicted during test under monotonic loading were ductility e_u and displacement corresponding to characteristic resistance e_k . Method of their determination is presented in Figure 5.

Parameter e_k (displacement corresponding to characteristic resistance R_k) was introduced in order to define a

reference value of deformation for development of cyclic test loading history. It represents a level of displacement corresponding to a characteristic resistance R_k at the stage of load increase. This parameter was determined for three material core thicknesses (S1÷S3) as a mean value obtained in each group. Another parameter is fastening ductility e_u . This property is defined as the deformation of the connection at the level of the characteristic resistance R_k at the stage of load decrease. In accordance with previously discussed properties, the parameter was determined for all thicknesses separately and calculated as a mean value in each group.

The shear flexibility of the fastening c_h was also calculated from monotonic tests results according to the ECCS recommendations [4]:

$$c_h = \frac{1}{R_d/\gamma_1} \cdot \frac{\sum a_h}{n} \quad (2)$$

where R_d is design resistance of a fastener ($R_d = R_k/\gamma_{M2}$), a_h is slip fastening at load equivalent to R_d/γ_1 , n is number of test specimens and γ_1 is partial factor.

The shear flexibility of fastenings was determined at two levels of load factor $\gamma_1 = 1.0$ (no reduction) and $\gamma_1 = 1.5$ (which stands for wind load partial factor). The values differed in three groups and showed increase along with the sheet thickness (Table 3).

Table 3: Shear flexibility of the fastenings from monotonic test results.

Group	Flexibility with partial factor $\gamma_1 = 1.0$, $c_{h,10}$ [mm/kN]	Flexibility with partial factor $\gamma_1 = 1.5$, $c_{h,15}$ [mm/kN]
S1	0.13	0.12
S2	0.15	0.14
S3	0.15	0.14

The great majority of tested connections under monotonic loading showed similar signs of failure. In the first stage of loading, an increasing inclination of both self-drilling screws was observed. The values of the fasteners' inclination, estimated from the photos taken at the level of 3 mm deformation, vary between 15° and 25° (Figure 6a). According to the ECCS recommendations [4], the inclination of more than 10 degrees, measured at the unloaded specimen, can be regarded as a failure of the substructure. This observation leads to a conclusion that the tested connections might fail before reaching the limit of 3 mm deformation. However, the tests were conducted continuously beyond the reference value, which made the estima-

tions rather demonstrative. The hole elongation was also observed from the side of a screw shank. Signs of piling of the sheets material were noticed in a majority of specimens during the test progression. Early symptoms of curling of the sheets were also observed in less than a half of all tests. In reference to [4], the behavior of the connections observed within 3 mm of relative displacement range showed bearing failure.

The deformations of the connection beyond the 3 mm of relative displacement showed an increase of fasteners inclination, which was followed by curling of the sheets edges and consecutively pull-out of the fasteners, (Figure 6b). In this case, the characteristics observed after the reference value of 3 mm deformation can be compared to a tilting and pull-out of failure, featured in [4].

Figure 6: Failure mode of specimen from S2 group; a) captured at the reference displacement value of 3 mm; b) beyond the reference displacement value of 3 mm.

3.2 Deterioration of resistance

The deterioration of the mechanical parameters of the connection under variable loads can be described as a decrease (or increase) of the particular quantity along with the subsequent repeated cycles, while the range of loading is not changing. Such signs of degradation were observed during all variable loading histories, Figure 7.

In order to evaluate the deterioration of the fastening's resistance, a $\varepsilon(\Delta e)$ parameter was introduced. It represents a ratio of the force value obtained in the last, third repeated cycle $F_{i,3}$ at the given range of displacement Δe , to the force value obtained in the first cycle of loading $F_{i,1}$ at the same range of displacement Δe :

$$\varepsilon(\Delta e) = F_{i,3}/F_{i,1} \quad (3)$$

where i is index of subsequent three block cycles.

Figure 7: Load-deformation response of the S2 group under variable loading histories: a) cyclic according to ECCS; b) repeated with displacement control, c) repeated with force control, d) repeated with overload.

Table 4: Deterioration of resistance $\varepsilon(\Delta e)$ for V1, V2 and V4 loading histories.

Loading history	V2			V1			V4
Normalized displacement range Δe [-]	0.25	0.5	1.0	2.0	4.0	6.0	0.5
S1	1.00	1.00	0.96	0.95	0.93	0.92	0.07
S2	0.97	0.96	0.92	0.92	0.87	0.88	0.00
S3	0.96	0.96	0.95	0.91	0.89	0.68	0.00

Prediction method of resistance deterioration is depicted in Figure 8.

Figure 8: Method of prediction $F_{i,3}$ and $F_{i,3}$ values (maximum forces in the first and third cycle at the same range of displacement Δe) as a part of evaluation of the $\varepsilon(\Delta e)$.

The resistance deterioration (resistance drop) parameter $\varepsilon(\Delta e)$ was calculated in all groups of specimens, for few ranges of displacement (Δe), based on the loading histories V1 and V2. The range of displacement (Δe) is normalized to displacement corresponding to characteristic resistance e_k :

$$\Delta e = (e_{i,max} - e_{i,min})/e_k \quad (4)$$

where $e_{i,max}$, $e_{i,min}$ are maximum and minimum values of displacement at given block of loading.

In loading history V4, where only third cycle differed from others, the deterioration of resistance was determined at only one range of displacement $\Delta e = (1,0e_k - 0,5e_k)/e_k = 0,5$. In this particular case, the resistance drop was calculated as ratio of the value of decreased force in the very last cycle to the force value obtained in the first cycle $\varepsilon(\Delta e = 0,5) = F_9/F_1$.

Obtained results of resistance drop ratio $\varepsilon(\Delta e)$ are shown in Figure 9 as function of relative range of displacement Δe and in Table 4.

The deterioration of connections was also observed as a increase of elongations along with the subsequent cycles

Figure 9: Deterioration of resistance $\varepsilon(\Delta e)$ evaluated from variable V1 and V2 loading histories. **Figure 10:** Method of prediction $e_{i,1}$ and $e_{i,3}$ values (maximum displacement in the first and third cycle at the same force range ΔF) as a part of evaluation of the $\varepsilon(\Delta F)$ for V3 loading history.

at equal force range, under repeated loading under force control (V3 loading history), Figure 10. This phenomenon was described by $\varepsilon(\Delta F)$ parameter, which is a ratio of the maximum displacement value obtained in the third performed cycle $e_{i,3}$ to the displacement in first cycle $e_{i,1}$ at the same force range ΔF .

$$\varepsilon(\Delta F) = e_{i,3}/e_{i,1} \quad (5)$$

The implementation of this parameter was dedicated to the assessment of results from V3 loading history only. Obtained results are shown in Figure 11 and Table 5. The force range ΔF is normalized to characteristic resistance of fastener R_k :

$$\Delta F = (F_{i,max} - F_{i,min})/F_k \quad (6)$$

Figure 11: Increase of elongation $\varepsilon(\Delta F)$ evaluated from variable V3 loading history.

Table 5: Increase of elongation $\varepsilon(\Delta F)$ for V3 loading history.

Normalized force range ΔF [-]		0.25	0.5	0.6
Group	S1	1.02	1.04	1.10
	S2	0.98	1.02	1.07
	S3	1.02	1.04	1.09

3.3 Deterioration of flexibility

Repeated nature of loading was expected to induce the connections' flexibility decrease in subsequent cycles. This phenomenon has a crucial meaning for both stressed skin designed elements and also for moment connections, where stiffness of the fastening determines the applicability of certain solution. A deterioration of flexibility is presented as a parameter $\xi(\Delta e)$, which stands for a ratio of flexibilities obtained from the third repeated cycle $c_{h,i,3}$ at the given displacement range Δe , to the flexibility $c_{h,i,1}$ obtained in the first cycle of loading at the same range of displacement Δe , (see Figure 12):

$$\xi(\Delta e) = c_{h,i,3} / c_{h,i,1} \quad (7)$$

Figure 12: Method of prediction $c_{h,i,1}$ and $c_{h,i,3}$ values (flexibilities in the first and third cycle at the same displacement range Δe) as a part of evaluation of the $\xi(\Delta e)$.

In all cases flexibilities $c_{h,i,j}$ were predicted in half-cycles corresponding to increasing load, as a ratio of recorded displacement range to force range, Figure 12. The force range was the difference between upper and lower force levels recorded during the tests. Upper force level was constant, and equal to R_d/γ_1 . Lower force level was equal to zero, where unloading branch of half-cycle intersected the abscissa. Otherwise was equal the minimum value obtained during unloading. The range of displacement was predicted in the similar way.

The parameter $\xi(\Delta e)$ was evaluated for results obtained from V1 and V2 loading histories, where the actuator was controlled by a displacement. The flexibilities were calculated referring to two levels of load factor γ_1 , as described in the monotonic test evaluation. Consequently, the deterioration of flexibility was evaluated in all groups of thicknesses. The results of the aforementioned calculations are presented in Figure 13-14, and in Tables 6-7 in reference to relative displacement Δe (compare eq. (4)).

Figure 13: Deterioration of flexibility $\xi(\Delta e)$ versus relative displacement Δe , evaluated from V1 and V2 loading histories at the load factor $\gamma_1 = 1.0$.

Table 6: Deterioration of flexibility $\xi(\Delta e)$ for V1, V2 loading histories at the load factor $\gamma_1 = 1.0$.

Loading history		V2			V1	
Normalized displacement range Δe [-]		0.25	0.5	1.0	2.0	4.0
Group	S1	0.57	0.99	1.13	1.07	1.13
	S2	0.69	1.14	1.08	1.19	1.49
	S3	0.48	1.21	1.15	1.34	3.12

From comparison of Table 6 and 7 it can be seen, that upper force level (R_d/γ_1 , where $\gamma_1 = 1.0$ and $\gamma_1 = 1.5$)

Figure 14: Deterioration of flexibility $\xi(\Delta e)$ versus relative displacement Δe , evaluated from V1 and V2 loading histories at the load factor $\gamma_1 = 1.5$.

Table 7: Deterioration of flexibility $\xi(\Delta e)$ for V1, V2 loading histories at the load factor $\gamma_1 = 1.5$.

Loading history	V2			V1		
	0.25	0.5	1.0	2.0	4.0	0.5
Normalized displacement range Δe [-]						
S1	0.67	0.85	1.12	1.12	1.15	1.88
Group S2	0.73	1.14	1.13	1.3	1.64	1.19
S3	0.57	1.26	1.21	1.52	3.72	1.7

utilized in flexibility calculations in given displacement range Δe has rather minor effect on parameter $\xi(\Delta e)$.

4 Summary and conclusions

The paper presents results of experimental study how variable load deteriorates structural properties of lap shear connections with self-drilling screws. One monotonic and four variable loading histories were utilized, with displacement and force control. Variable loading histories have pulsating character in tension range. Due to small bending stiffness application of compression force or cyclic loading pattern were impossible.

The deterioration of structural properties under variable loads was predicted as a decrease of resistance and increase flexibility along with the subsequent repeated cycles. It was observed that generally deterioration of resistance and flexibility is directly proportional to range of displacement in case of displacement control of loading. Similarly, deterioration level is directly proportional to force range in case of force control of loading.

Resistance drop ratio is rather small in case of minor range of displacement. In case of displacement range $\Delta e = 1.0e_k$ degradation of resistance reaches 91-96% of its

initial value. When displacement range increases to $\Delta e = 6.0e_k$ degradation reaches 68-92%. Very dangerous for resistance is repeated history of loading with overload in one cycle. Resistance of connector radically drops for given displacement level.

In case of flexibility, at small displacement range $\Delta e = 0.25e_k$ fastenings become stiffer. Degradation of flexibility starts to increase at larger displacement range.

Dependence between deterioration level and thickness of sheets in tested connections is visible in medium range of displacement ($\Delta e = 2.0 \div 4.0e_k$) – the thicker the sheet, the degradation is greater. Maybe such dependence is related with ductility of connections.

Results obtained in this study are related to connections of sheeting loaded in tension, but the same phenomena can occur in cold-formed frame corners, where self-drilling screws are used as site connections of moment resisting joints.

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