Analysis of the resistance of thin-walled cold-formed compressed steel members with closed cross-sections. Part 1

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Key words: thin-walled web; cold-formed profiles; initial imperfections

The paper is divided into two parts. Part 1 presents fundamental information about experimental-theoretical research oriented to determinate the resistance of thin-walled compressed steel members. The investigated members had closed cross-sections made from homogeneous materials. The theoretical analysis in this research is oriented to determinate the resistance of mentioned members according to European and Slovak standards, while the experimental investigation is to verify the theoretical results and to investigate the behaviour of mentioned members during the loading process. Part 2 will be focused on the numerical analysis of the results, as well as on the 3D modelling and simulation of experimental tests.

Introduction

Theory and design development of steel thin-walled cold-formed members and profiles creates a certain knowledge base for their practical application in civil engineering. A lot of researches and studies have been devoted to this field [1–5]. Some of them were focused on the closed cross sections [6–9], other studies investigated the resistance of members with open profiles [10–14]. However, this fact does not mean that all complex and challenging processes of the behaviour of thin-walled cold-formed members during the loading procedure are sufficiently investigated.

From the material and geometric point of view, the thin-walled cold-formed profiles have specific specialties, which their design must responsibly take into account. In the terms of their resistance, an important issue is the effectiveness of mutual interaction between several webs. The local stability requirements related to unfavourable buckling effects of their compressed parts are very significant. Favourable effects, related to membrane stresses and post-critical behaviour are also important. Different calculation procedures with different results in the relevant standards (previous National standard STN 73 1402:1988 and new European standard EN 1993-1-3: 2006) and their confrontation with experimental results indicated the need for further investigation of post-critical behaviour of these members.

The indicated issues are generally problematic, both from the theoretical and practical aspects, therefore the presented research aims to investigate the interaction between individual webs and local resistance of compressed thin-walled steel members with closed cross-sections without longitudinal stiffeners [15].

Experimental program and tested members

The experimental research program includes 17 thin-walled cold-formed test members having closed cross-sections with different dimensions, advisable chosen to eliminate the global stability problems, to reflect the post-critical behaviour of the individual thin webs and to present the interaction of the adjacent parts in the loading and failure processes. The test members were divided into two cross-sectional groups (A and B). Group A consists of members having closed square cross sections, while Group B is created by members with closed rectangular cross-sections. The research program of test members and designed geometrical dimensions of individual groups are given by Table 1. Basic schemes of the test members are illustrated in Figures 1 and 2. Table 2 presents the basic geometrical characteristics for the individual groups of test members, determined according to relevant standards; EN 1993-1-3 and STN 731402.

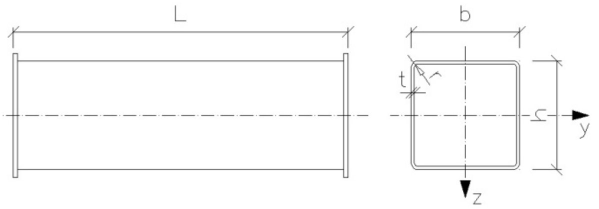

Figure 1. Scheme of the test members; group A

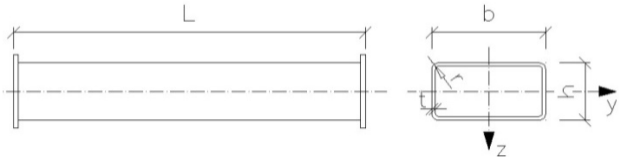

Figure 2. Scheme of the test members; group B

Table 1. Geometrical dimensions of the designed test members

Tested members			Geometrical dimensions [mm]					Steel
Cross-sectional group		Marking	b	h	t	r	L	
A	1	A11, A12	100	100	2	3	300	S235
	2	A21, A22, A23	150	150			450	
	3	A31, A32, A33	200	200			600	
B	1	B11, B12, B13	150	100			450	
	2	B21, B22, B23	200	100			650	
	3	B31, B32, B33	200	150			600	

Table 2: Geometrical characteristics of the designed test members

Cross-sectional group		EN 1993-1-3:2006				STN 73 1402:1988			
		β_{wb}	β_{wh}	λ_y	λ_z	β_{wb}	β_{wh}	λ_y	λ_z
A	1	48,12	48,12	7,50	7,50	46,00	46,00	7,52	7,52
	2	73,12	73,12	7,45	7,45	71,00	71,00	7,46	7,46
	3	98,12	98,12	7,42	7,42	96,00	96,00	7,44	7,44
B	1	73,12	48,12	10,70	7,87	71,00	46,00	10,74	7,89
	2	98,12	48,12	15,01	8,84	96,00	46,00	15,05	8,85
	3	98,12	73,12	9,58	7,71	96,00	71,00	9,60	7,72

In the terms of local stability classification, the webs of individual cross-sections are thin-walled at the compression loading (β_{wh}, β_{wb}). From the global stability point of view, all of tested members are designed as compact (slenderness λ_y, λ_z) in order to define the local (cross-sectional) resistance.

All tested members are made from steel sheets with nominal thickness 2 mm. Three material samples were taken from each steel sheet to make normative shaped test specimens. The test specimens underwent the tension tests to find the stress-strain diagrams and material properties. Detailed dimension measuring of the test members was done before the loading tests, in order to consistent evaluation of the experimental results. The averages of measured values are presented in Table 3.

The dimensions of cross-sections: width *b*, height *h*, and thickness *t* were measured on the top, middle and bottom of each member. The radius *r* was measured at each curved corner and the length *L* was measured at each member's side. Based on the obtained average values of the individual dimensions, the actual geometrical characteristics of the designed test members were determined.

Table 3. Average dimensions values and actual material characteristics

Tested member	b	h	t	r	L	f_y	f_u
	[mm]					[MPa]	
A11	105,80	103,87	2,12	3,0	300,98	240,67	360,00
A12	105,50	103,92	2,12	3,0	300,68	240,67	360,00
A21	154,80	155,12	2,16	3,0	450,20	241,00	358,33
A22	154,22	153,73	2,10	3,0	450,63	241,00	358,33
A23	153,80	153,73	2,11	3,0	448,83	241,00	358,33

Tested member	b	h	t	r	L	f_y	f_u
	[mm]					[MPa]	
A31	208,45	202,85	2,13	3,0	599,75	236,67	355,67
A32	206,50	203,25	2,10	3,0	600,00	236,67	355,67
A33	206,72	203,07	2,10	3,0	600,00	236,67	355,67
B11	157,12	102,52	2,11	3,0	450,70	241,00	360,67
B12	157,93	102,43	2,11	3,0	450,03	241,00	360,67
B13	159,37	101,83	2,11	3,0	450,03	241,00	360,67
B21	207,93	103,08	2,12	3,0	650,00	242,33	360,00
B22	207,47	103,18	2,10	3,0	649,88	242,33	360,00
B23	207,35	102,62	2,16	3,0	649,25	242,33	360,00
B31	206,98	152,57	2,10	3,0	600,25	240,00	358,33
B32	207,13	152,50	2,11	3,0	599,75	240,00	358,33
B33	206,90	153,13	2,14	3,0	599,50	240,00	358,33

Testing methodology, results and their analysis

The tests were made to get detailed information about strain, failure and ultimate loads of the tested members, considering their actual geometrical and material parameters. In accordance with the research target, the emphasis has been imposed on the post-critical behaviour and interaction of the individual thin webs. In this context, the initial imperfections of slender webs are significant for the experimental results valuation and connected theoretical analyses. Therefore, the initial buckling shapes of all test members' webs were measured using previously generated raster, by means of inductive sensors before initiating testing.

Figure 3 illustrates the concept of the generated raster and general view of the test. For illustration, the values of measured initial imperfections in individual raster points of the test member B22 are shown in Table 4.

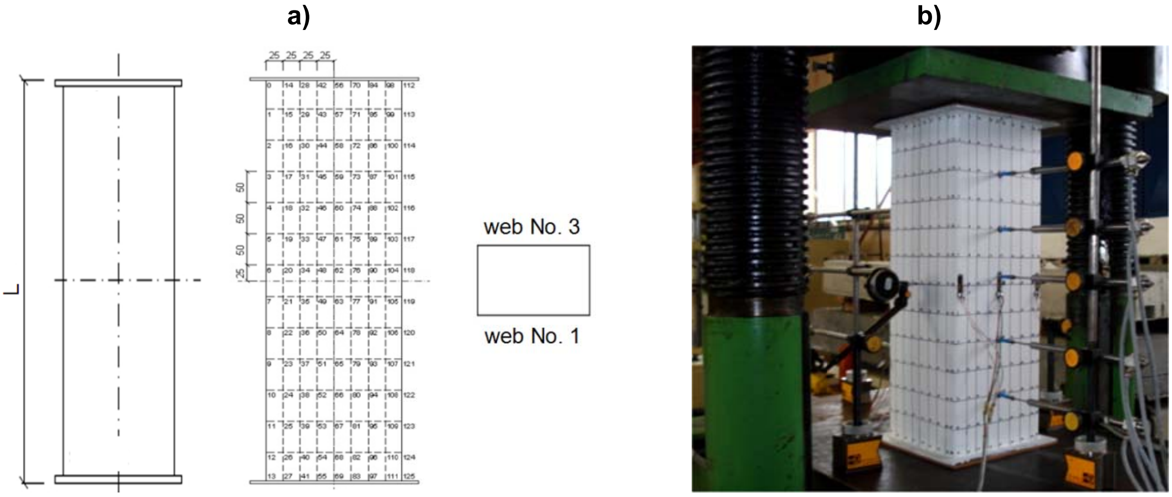

Figure 3: a) generated raster; b) general view of the test

During consecutive programmed loading of the tested members, the strains ε were measured using resistive strain-gauges in the middle cross-sections; deflections (buckling) of the webs *w* were measured using inductive sensors in different places, according to members lengths – see Figure 3. The resistive strain-gauges and inductive sensors were connected to the computer for direct evaluation. The loading process of each member was regulated close to its real behaviour, measured strains ε and deflections *w*. The test continued until total failure, defined by the beginning of continuous increasing strains ε and displacements of the webs *w*. The final buckling shapes after the test was finished were also revealed [16]. Examples of the test completion and overall failure of the tested member are illustrated in Figure 4.

Table 4. Positions and values of initial imperfections; test member B22, web No. 1

Raster point	Values [mm]	Raster point	Values [mm]	Raster point	Values [mm]	Raster point	Values [mm]	Raster point	Values [mm]	Raster point	Values [mm]	Raster point	Values [mm]	Raster point	Values [mm]	Raster point	Values [mm]
0	+0,00	14	+0,20	28	+0,25	42	+0,19	56	+0,15	70	+0,02	84	-0,13	98	-0,37	112	-0,40
1	+0,04	15	+0,17	29	+0,18	43	+0,08	57	+0,10	71	+0,01	85	-0,09	99	-0,28	113	-0,40
2	+0,06	16	+0,13	30	+0,11	44	-0,01	58	-0,01	72	-0,07	86	-0,10	100	-0,29	114	-0,40
3	-0,12	17	+0,01	31	+0,01	45	-0,14	59	-0,12	73	-0,19	87	-0,21	101	-0,37	115	-0,41
4	-0,24	18	-0,19	32	-0,15	46	-0,25	60	-0,25	74	-0,31	88	-0,38	102	-0,49	116	-0,63
5	-0,39	19	-0,25	33	-0,19	47	-0,32	61	-0,33	75	-0,37	89	-0,46	103	-0,55	117	-0,56
6	-0,59	20	-0,29	34	-0,19	48	-0,28	62	-0,36	76	-0,36	90	-0,43	104	-0,53	118	-0,69
7	-0,50	21	-0,36	35	-0,27	49	-0,33	63	-0,33	77	-0,37	91	-0,44	105	-0,55	119	-0,53
8	-0,63	22	-0,57	36	-0,36	50	-0,44	64	-0,50	78	-0,44	92	-0,50	106	-0,55	120	-0,64
9	-0,93	23	-0,74	37	-0,61	51	-0,59	65	-0,61	79	-0,54	93	-0,60	107	-0,66	121	-0,63
10	-0,83	24	-0,89	38	-0,80	52	-0,78	66	-0,82	80	-0,75	94	-0,72	108	-0,76	122	-0,86
11	-1,20	25	-1,11	39	-1,02	53	-1,03	67	-1,03	81	-0,96	95	-0,91	109	-0,86	123	-0,79
12	-1,25	26	-1,25	40	-1,19	54	-1,24	68	-1,17	82	-1,11	96	-1,05	110	-0,98	124	-0,83
13	-1,51	27	-1,44	41	-1,20	55	-1,17	69	-1,13	83	-1,07	97	-1,06	111	-1,00	125	-0,87

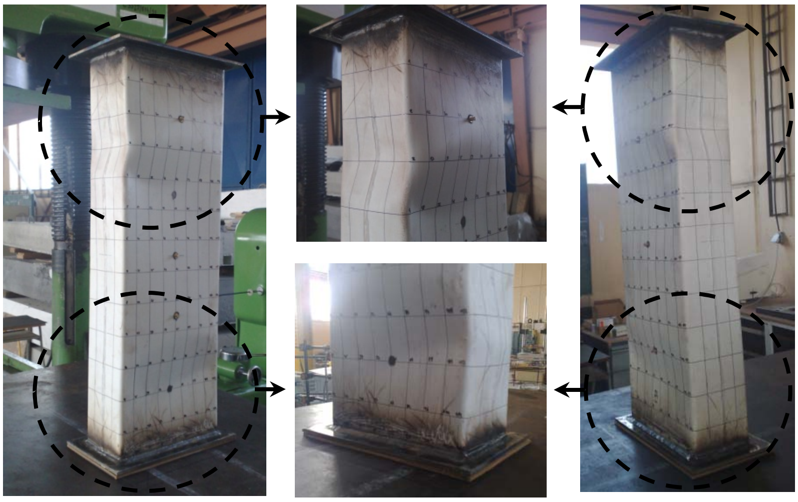

Figure 4. Test completion and overall failure; member B22

Taking into account the real-measured dimensions and yield stresses, the limit loads of all tested members were calculated according to relevant standards [17–20]. Theoretical and experimental limit loads are presented in Table 5.

Table 5. Theoretical and experimental limit loads of all tested members

Member	$N_{pl,STN}$	$N_{pl,EN}$	$N_{ul,el,STN}$	$N_{ul,el,EN}$	$N_{u,y,STN}$	$N_{u,y,EN}$	$N_{u,z,STN}$	$N_{u,z,EN}$	$N_{u,exp}$
	[kN]								
A11	206,67	204,02	193,54	177,92	193,54	177,92	193,54	177,92	164,77
A12	206,42	203,76	193,26	177,84	193,26	177,84	193,26	177,84	155,20
A21	315,64	312,94	225,41	206,80	225,41	206,80	225,41	206,80	-
A22	304,84	302,20	214,63	196,18	214,63	196,18	214,63	196,18	181,78
A23	306,01	303,36	216,29	197,99	216,29	197,99	216,29	197,99	178,59
A31	407,36	404,74	232,21	209,85	232,21	209,85	232,21	209,85	189,22
A32	400,55	397,96	225,66	204,70	225,66	204,70	225,66	204,70	195,59
A33	400,59	397,99	225,83	204,70	225,83	204,70	225,83	204,70	186,03

Member	$N_{pl,STN}$	$N_{pl,EN}$	$N_{ul,el,STN}$	$N_{ul,el,EN}$	$N_{u,y,STN}$	$N_{u,y,EN}$	$N_{u,z,STN}$	$N_{u,z,EN}$	$N_{u,exp}$
	[kN]								
B11	257,27	254,62	217,26	187,42	217,26	187,42	217,26	187,42	159,45
B12	258,02	255,36	217,45	187,51	217,45	187,51	217,45	187,51	165,83
B13	258,19	255,55	216,69	186,66	216,69	186,66	216,69	186,66	158,39
B21	312,08	309,40	229,30	194,45	229,30	194,45	229,30	194,45	171,15
B22	309,28	306,62	226,30	191,76	226,30	191,76	226,30	191,76	173,27
B23	316,63	313,93	234,79	200,55	234,79	200,55	234,79	200,55	164,77
B31	355,59	352,96	234,82	201,00	234,82	201,00	234,82	201,00	195,59
B32	356,61	353,97	235,94	201,98	235,94	201,98	235,94	201,98	184,97
B33	363,52	360,86	243,57	208,89	243,57	208,89	243,57	208,89	204,10

N_{pl} – the local plastic limit load of the full cross-section, defined by attaining the yield stress f_y ;
$N_{ul,el}$ – the local (post-critical) elastic limit load of the effective cross-section, defined by attaining the yield stress f_y;
$N_{u,y(z)}$ – the buckling limit load to the axes *y* and *z*, considering the effective cross section.

The graphic evaluation and comparison of the theoretical limit loads and experimental limit loads are presented in Figure 5.

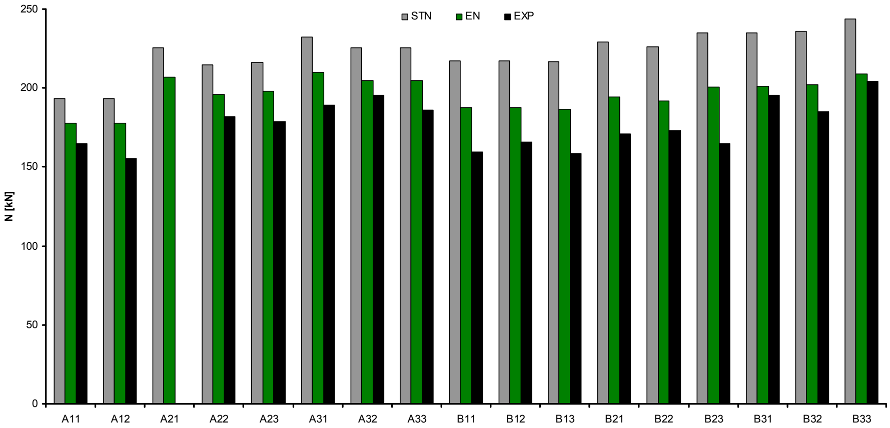

Figure 5. Limit loads of tested members; cross-sectional groups A and B

From Table 5 and Figure 5 it is evident that the theoretical limit loads, calculated according to the relevant standards are different. It is also evident that the experimental limit loads are smaller in all cases.

Conclusion

1. The differences in the results, calculated according to standards STN 73 1402:1998 and EN 1993-1-3:2006, are about 18%. This may be caused by different procedures for the calculation of cross-sectional characteristics at which EN 1993-1-3:2006 allows simplifying the procedure of their calculation.
2. The experimental limit loads are smaller than those limit loads, calculated according to standards EN 1993-1-3:2006 by 12%–24%. This serious fact may occur as a consequence of the unfavourable development of initial imperfections.
3. In terms of tolerance values, the maximum measured imperfection of the webs was smaller than the maximum tolerated value, given in the standard EN 1090-2+A1 [21] as b/50. Although this condition has been met, the results revealed a serious effect of initial imperfections.
4. The resistances of the tested members coupled with their post-critical behaviour were investigated by means of theoretic-numerical analysis and experimental verification. Based on obtained results we can assert that the resistance of the compressed thin-walled cold-formed steel members is significantly influenced by the initial imperfections and/or by the initial buckling shapes of their individual webs.

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Ал Али М., Томко М., Бадак М. Расчет сопротивления сжатых элементов легких стальных тонкостенных конструкций закрытого профиля. Часть 1

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