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THE ELASTIC-PLASTIC BEARING CAPACITY INVESTIGATION OF THIN-WALLED STEEL MEMBERS WITH QUASI-HOMOGENOUS AND COMBINED CROSS-SECTIONS

The paper presents fundamental information about realized experimental-theoretical research to determine the load-carrying capacities for thin-walled compressed steel members with quasi-homogenous and hybrid cross-sections. The webs of such members are stressed in the elastic-plastic region. The research joins on previous research of the first author of the paper [1]. The aim of this research is to investigate and analyze the elastic-plastic post-critical behavior of thin web and its interaction with flanges. Some experimental results are presented in the paper.

Introduction. The continued effort for economic design of steel structures lead to decrease their weight by shape and material optimalization, which lead to use the high-stress steels combined with standard structural steels. The efficiency of high-stress steels using and their combination with standard structural steels is evident in case of bending members – beams mostly subjected to bending loading. From the complex optimalization analyses follow, that the high-stress steels combined with standard structural steels may be also advantage in case of members subjected to compression loading, mainly in case of thin-walled members. This paper presents basic information about ongoing experimental/theoretical research of elastic-plastic bearing capacities of thin-walled compression steel members with quasi-homogenous and combined cross-sections. This research program is resulting on previous research of first author of this paper [1]. This research is distinctively oriented on the investigation and analyses of post-critical behavior and interaction of slender/ultra-slender web with flanges in the process of their transformation and failure.

The research experimental program and testing members. The experimental research includes the testing of 24 welded compression steel models/members having quasi-homogenous and combined I cross-sections with different dimensions, advisable elected to show, in decisive extent, the elastic-plastic post-critical effect of slender webs and their interaction with flanges in process of their strain, transformation and failure. Table 1 presents the total research program, designed geometrical dimensions and designed materials for flanges and webs of several testing models/members groups. Scheme of testing models/members is illustrated in figure 1. Basic geometrical and material characteristics of several designed testing models/members are presented in table 2.

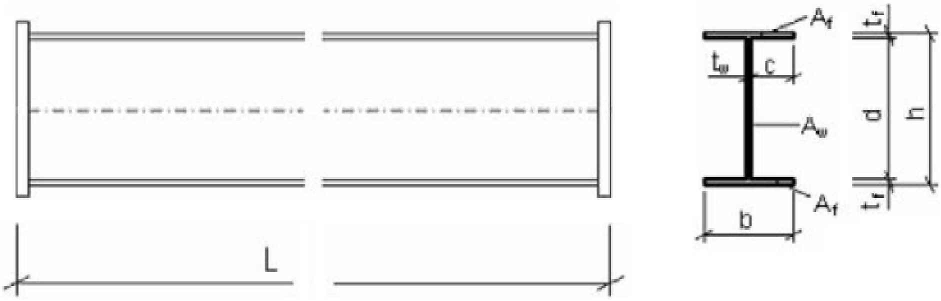

Fig. 1. Scheme of testing models/members

Table 1

The total research program, geometrical dimensions and materials of flanges and webs of testing models

Testing models/members			Geometrical dimensions [mm]						Steel	
M.G.	C.G.	Marking	L	h	b	tf	d	tw	flanges	webs
A	1	AS11, AS12, AS13	250	112	60	6	100	2	S235	
	2	AS21, AS22, AS23	500	212	90		200			
	3	AS31, AS32, AS33	750	312	120		300			
	4	AS41, AS42, AS43	1000	412	150		400			
B	1	BS11, BS12, BS13	250	112	60		100		S355	S235
	2	BS21, BS22, BS23	500	212	90		200			
	3	BS31, BS32, BS33	750	312	120		300			
	4	BS41, BS42, BS43	1000	412	150		400			

Table 2

Basic geometrical and material characteristics of designed testing models/members

Members		Geometrical characteristics					Material characteristics
M.G.	C.G.	$\lambda_y = L / i_y$	$\lambda_z = L / i_z$	$\beta_f = c / t_f$	$\beta_w = d / t_w$	$\gamma = A_w / A$	$m_y = f_{yf} / f_{yw}$
A	1	5,03	16,02	4,83	50,0	0,217	1,000
	2	5,01	20,80	7,33	100,0	0,270	
	3	4,99	23,02	9,83	150,0	0,294	
	4	4,98	24,28	12,33	200,0	0,308	
B	1	5,03	16,02	4,83	50,0	0,217	1,511
	2	5,01	20,80	7,33	100,0	0,270	
	3	4,99	23,02	9,83	150,0	0,294	
	4	4,98	24,28	12,33	200,0	0,308	

All of testing models/members are divided to 2 material groups (M.G.: A, B) and 4 cross-sectional groups (C.G.: 1, 2, 3, 4). The materials group A is created by members with homogenous cross-section made from steel S235 and group B is created by members with combined cross-section made from steel S355 (flanges) and S235 (webs). The several cross-sectional groups have different dimensions, but first of all have different web slenderness β_w. It is apparently, that the members are thin-walled at the compression loading. At the same time, according to local stability aspects, the flange dimensions are designed to be compact (slenderness β_f), when subjected to elastic loading. At last, according to global stability aspects and dimensions of several cross-sectional groups, the lengths of members L are designed to be quasi-compact (slenderness λ_z, $\lambda_z > \lambda_y$). The ratio γ give an evident characteristic of the economic efficiency of designed cross-sections – table 2.

The flanges of all members were made out from 2 sheets, 6 mm thick (steel S235 and S355) and the webs from 2 sheets, 2 mm thick (steel S235). Three material specimens were taken form each of used sheet to make normative shaped testing bars. The testing bars underwent a tension tests to find out the strain-stress diagrams and required material characteristics. Characteristic strain-stress diagrams are illustrated in figure 2, where the values of averaged determined yield stress f_y and ultimate tensile strength f_u are presented. Mentioned yield stresses f_y and ultimate tensile strength f_u was assign to the relevant flanges and webs of several members, table 3.

For consistent evaluation and analyses of experimental knowledge and results, it is also necessary to know the real geometrical dimensions of the testing models/members. Therefore and before testing beginning, the detailed dimension measuring of all members was done. Dimensions of cross-sections: height *h*, width *b*, thicknesses of flanges t_f and webs t_w was measured on the top, middle and bottom of each member. Averaged values of measured dimensions are considered as real. These values together with the measured members' lengths L are presented table 3.

Table 3

Determined dimensions of testing models/members and the yield stresses fy of the flanges and webs

Members	L	h	b	t_f	d	t_w	f_{yf}	f_{yw}	f_{uf}	f_{uw}
	[mm]	[MPa]	[MPa]							
AS11	250,0	112,05	60,28	6,00	100,05	2,17	280,00	265,67	411,00	365,33
AS12	250,0	112,54	60,36	6,03	100,48	2,17	280,00	265,67	411,00	365,33
AS13	250,0	112,19	60,27	6,00	100,19	2,17	280,00	265,67	411,00	365,33
AS21	498,5	211,86	90,33	6,18	199,50	2,13	280,00	245,00	411,00	368,67
AS22	499,5	211,89	90,44	6,08	199,73	2,20	280,00	245,00	411,00	368,67
AS23	499,3	211,55	90,43	6,06	199,43	2,20	280,00	245,00	411,00	368,67
AS31	750,3	311,66	120,35	5,83	300,00	2,10	280,00	265,67	411,00	365,33
AS32	750,0	312,22	120,47	5,86	300,50	2,10	280,00	265,67	411,00	365,33
AS33	750,2	311,09	120,70	5,88	299,33	2,17	280,00	265,67	411,00	365,33
AS41	999,8	411,78	151,03	5,89	400,00	2,20	280,00	245,00	411,00	368,67
AS42	999,7	410,90	150,51	5,95	399,00	2,20	280,00	245,00	411,00	368,67
AS43	1000,3	410,92	150,51	5,96	399,00	2,20	280,00	245,00	411,00	368,67
BS11	250,0	112,09	60,14	6,11	99,87	2,20	383,00	265,67	551,67	365,33
BS12	250,0	113,05	60,68	6,25	100,55	2,25	383,00	265,67	551,67	365,33
BS13	250,0	112,27	60,36	6,22	99,83	2,17	383,00	265,67	551,67	365,33
BS21	500,2	211,80	90,08	6,09	199,62	2,20	383,00	245,00	551,67	368,67
BS22	499,3	211,62	90,42	6,06	199,50	2,20	383,00	245,00	551,67	368,67
BS23	500,3	211,47	90,78	5,90	199,67	2,20	383,00	245,00	551,67	368,67
BS31	750,2	311,34	120,00	5,92	299,50	2,10	383,00	265,67	551,67	365,33
BS32	750,0	311,36	120,45	5,93	299,50	2,13	383,00	265,67	551,67	365,33
BS33	750,2	311,36	120,28	5,93	299,50	2,10	383,00	265,67	551,67	365,33
BS41	999,6	411,50	150,40	5,93	399,63	2,20	383,00	245,00	551,67	368,67
BS42	1000,0	411,44	150,18	5,97	399,50	2,20	383,00	245,00	551,67	368,67
BS43	999,2	411,57	150,62	5,90	399,77	2,20	383,00	245,00	551,67	368,67

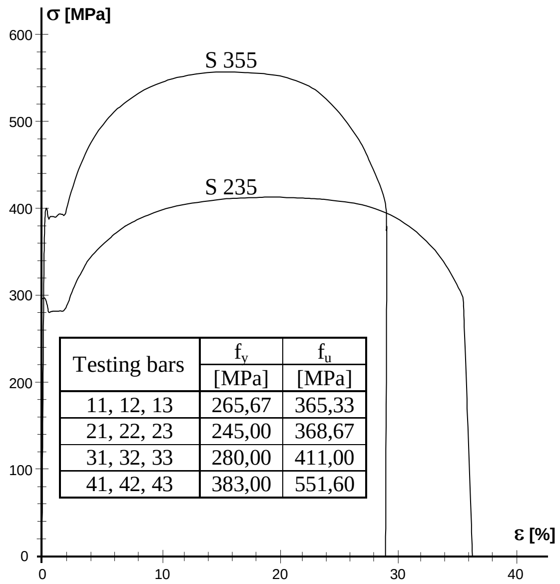

Fig. 2. Characteristic strain-stress diagrams and determined material characteristics

Figure 2 and table 3 show the good quality of testing members' material characteristics. Determined yield stresses f_y of their flanges and webs f_{yf} and f_{yw} are higher than the normative values. Also in the case of materials group A members with designed homogenous cross-sections (M.G. A), the determined flanges yield stresses f_y values are higher than the webs yield stresses, $f_{yf} > f_{yw}$. This means, that they are material combined (m_y = 1,054, event. 1,143). In the case of materials group B it is categorical go about members with material combined cross-sections (m_y = 1,442, event. 1,563). In the case of all testing bars a good material ductility was found, $A_5 > 29$ %.

Methodology and test content. The test have to bring out detailed investigation about overstrain, failure and gross bearing capacity of the above-mentioned members, in consider of several designed – geometrical and material parameters.

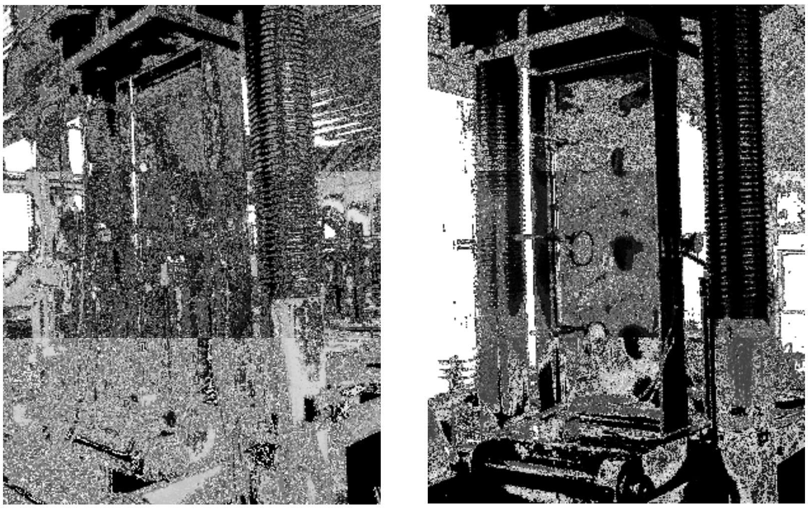

Fig. 3. General layout of the test, measurement of strains ε, deflections of the web w and buckling of member BS41

In accordance with research target, the emphasis is imposed on elastic-plastic post-critical behavior of slender webs and their interaction with flanges. In context with that, the initial shape deflections of members, mainly the initial buckling of slender webs are significant for the experimental results valuation and connected theoretical analyses. Therefore, before testing start the initial buckling of all members' webs are finding out on previously drawn raster by means of inductive sensors. The tests of members in compression are realized by means of press at the bearing structures laboratory. During consecutive programmed overloading of member, the strains ε in the middle cross-section are measured. Measurement is realized in 12 places, double-faced on the web in 6 places and also on the flanges in 6 places. The resistance tensiometers are used to measurement the strains ε by means of measuring apparatus Hottinger Balwin UPM 60 connected to computer for direct evaluation. According to member's length, the deflections of web w are measured in 3 or more places elected in the characteristic positions. The web deflections w are measured using inductive sensors connected to computer and also using mechanic gauges. In the case of members with ultra-slender webs (AS41 ~ AS43 and BS41 ~ BS43), the global buckling is also investigated in the middle cross-section on the edges of flanges. The member's global buckling v is measured by means of mechanic gauges. General layout of the test, measurement of strains ε and lateral deflections of the web w are illustrated in figure 3.

The members during the test are consecutively overloaded and released. The member overloading is regulated close to its behavior, measured values of strains ε and deflections of the web w. The test continue up to total failure, defined by the beginning of consecutive, continuous increasing of strains ε and deflections of the web w. Figure 4 illustrate the total failure of members AS22 a BS22 by local buckling of web and compression flanges.

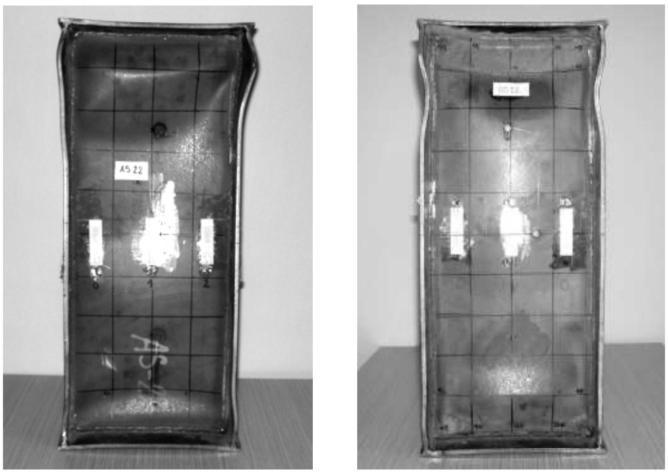

Fig. 4. The total failure of members AS22 a BS22 by local buckling of their webs and flanges

Partial theoretical and experimental results. According to procedures and formulae of first author the theoretical ultimate loading of all testing members were calculated as following [1]:

N_{el}	ultimate elastic loading definite by attaining the web yield stress f_{yw} of cross-section,
N_{pl}	ultimate plastic loading definite by attaining the flanges yield stress f_{yf} of cross-section,
$N_{ul,el}$	ultimate elastic post-critical loading definite by attaining the yield stress f_{yw} in the outer fibers of cross-sectional web,
$N_{ul,ep}$	ultimate elastic-plastic post-critical loading definite by attaining the ultimate strain $\varepsilon_u = \varepsilon_{yf}$ in the outer fibers of cross-sectional web,
$N_{u,y}$, $N_{u,z}$	ultimate buckling loading of member according to axis y and z considering the elastic-plastic post-critical behavior of the web.

The relevant values of several members' ultimate loadings are showing in table 4. All of members' ultimate loadings were calculated according to real – measured dimensions and determined yield stresses of their flanges and webs.

From the mutual comparison of several ultimate loading results:

– the strength benefit of material combination ($N_{el} \rightarrow N_{pl}$),

– the stability benefit of elastic-plastic behavior of the thin webs ($N_{ul,el} \rightarrow N_{ul,ep}$),

– the applicability of objective strength and stability design of members ($N_{ul,ep} \rightarrow N_{u,z}$).

In general, ultimate $N_{u,z}$ buckling loadings have the smallest values. However, these values are very close to the ultimate elastic-plastic post-critical loadings values – $N_{ul,el}$. When the real boundary conditions of members are considered in accordance with research target, the elastic-plastic post-critical interaction between thin webs and flanges may appear in conclusive rate.

Until this time 21 of 24 members were tested. All of tested members were failure by means of local failure of flanges in consequence of webs' local deflection in multiple waves with different shapes. Conclusive buckling of web and flanges was mainly concentrated in the ending areas of members – obviously because of concentrated loading transfer, figures 4 and 5. The interaction between web and flanges is evidently manifested here. Determined ultimate experimental loadings, eventually bearing capacities $N_{u,exp}$ are also illustrated in Table 4. Very good consonance can by found from the preliminary realized comparison between determined experimental bearing capacities $N_{u,exp}$ and theoretical ultimate loadings $N_{u,z}$, $N_{ul,ep}$. In the case of members with ultra-slender webs: BS42 a BS43 (β = 200) more significant differences was registered. Some of obtained experimental results and relations $N – w$ and $N – \varepsilon$ are illustrated in figures 5, 6 and 7.

Table 4

Theoretical ultimate loading a experimental bearing capacities of testing members

PRÚT	N_{el}	N_{pl}	$N_{ul,el}$	$N_{ul,ep}$	$N_{u,z}$	$N_{u,y}$	$N_{u,exp}$	$N_{u,exp}/N_{u,z}$ ($N_{u,exp}/N_{ul,ep}$)	
	[kN]								
AS11	249,9	260,2	249,9	260,2	260,2	260,2	278,0	1,068	1,065 (1,065)
AS12	251,3	261,8	251,3	261,8	261,8	261,8	275,0	1,050	
AS13	249,9	260,3	249,9	260,3	260,3	260,3	280,0	1,076	
AS21	377,6	416,7	322,8	360,9	356,1	360,9	357,0	1,003	1,021 (1,010)
AS22	377,1	415,6	321,9	359,2	354,3	359,2	373,0	1,053	
AS23	376,0	414,4	320,9	358,2	353,3	358,2	359,0	1,016	
AS31	540,2	560,3	424,5	444,8	435,6	444,8	447,0	1,026	1,003 (0,982)
AS32	542,8	563,0	426,8	447,2	438,1	447,2	432,0	0,986	
AS33	549,7	570,0	432,2	452,7	443,4	452,7	442,0	0,997	
BS11	253,6	339,8	253,6	339,8	335,5	339,8	357,0	1,064	1,053 (1,040)
BS12	261,6	350,6	261,6	350,6	346,5	350,6	363,0	1,048	
BS13	257,0	345,1	257,0	345,1	341,0	345,1	357,0	1,047	
BS21	376,4	527,8	321,2	469,2	454,9	469,2	466,0	1,024	1,062 (1,031)
BS22	376,0	527,3	320,9	468,7	454,7	468,7	492,0	1,082	
BS23	370,1	517,9	314,9	459,2	445,7	459,2	482,0	1,081	
BS31	544,6	711,3	429,2	597,0	569,9	592,8	565,0	0,991	0,993 (0,910)
BS32	549,0	716,6	432,6	595,0	574,3	597,2	577,5	1,006	
BS33	546,1	713,5	430,7	691,8	572,2	595,0	562,5	0,983	
BS41	643,0	888,2	486,7	691,8	659,5	691,8	657,5	0,997	0,937 (0,894)
BS42	654,7	902,1	494,4	709,2	676,1	709,2	590,0	0,873	
BS43	650,9	896,2	490,5	695,7	663,0	695,7	625,0	0,943	

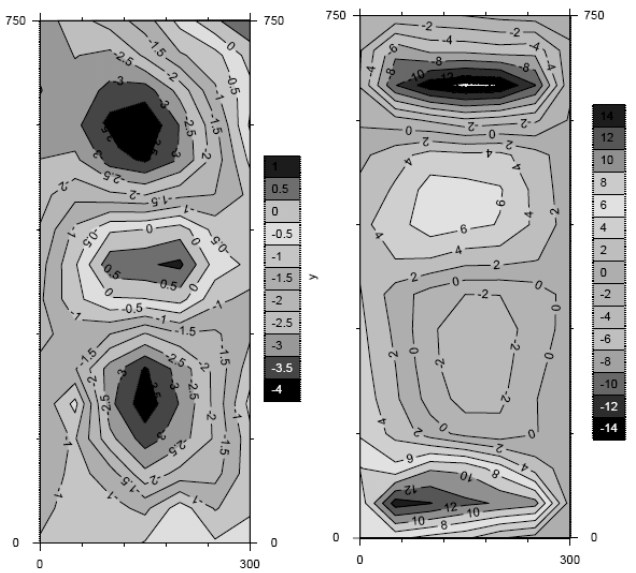

Fig. 5. Initial and final web buckling shapes of member AS31

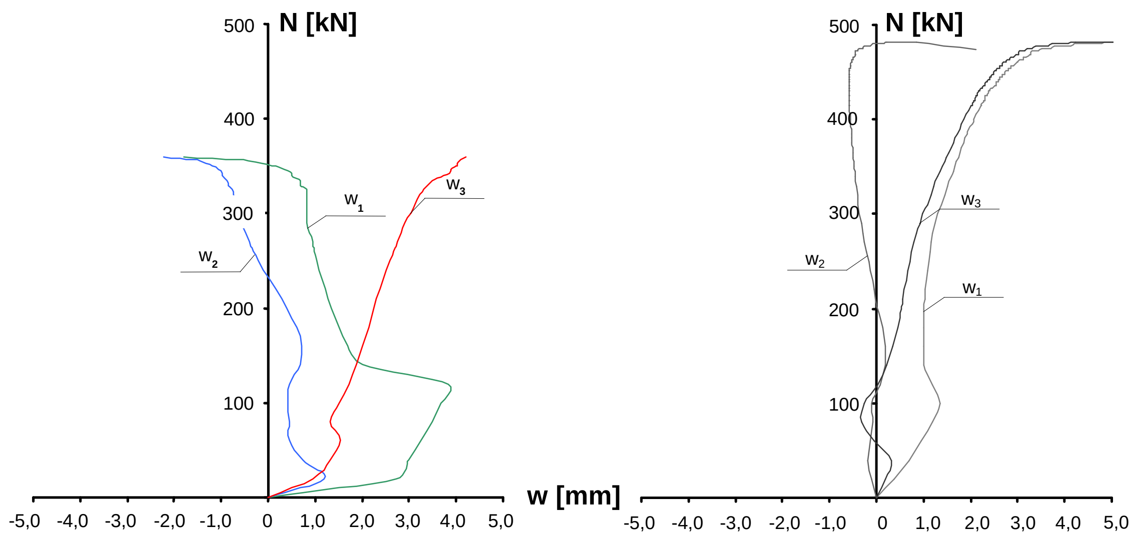

Fig. 6. The web deflections w in the middle and quarters of members AS 23 (left) and BS 23 (right)
w_1 – in the upper quarter, w_2 – in the middle, w_3 – in the lower quarter

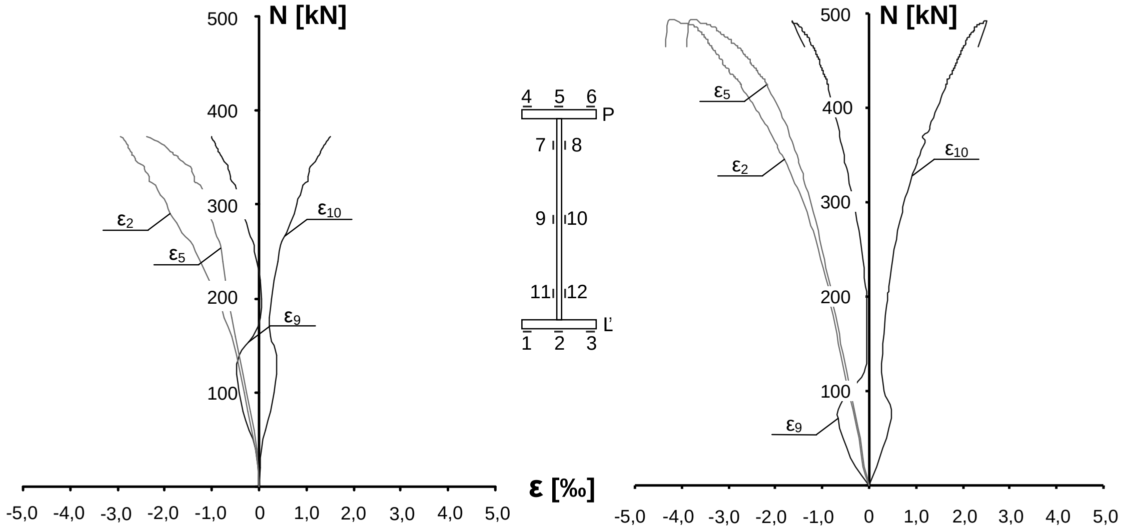

Fig. 7. The web and flanges strains ε - members AS 22 (left) and BS 22 (right)

Conclusion. This article informs about research of welded thin-walled compression steel members with quasi-homogenous and combined cross-sections. The research is successfully continued. Presented partial results affirm the knowledge and expand the results of the article first author, which were obtained during his previous research. The obtained experimental bearing capacities of members are in a good consonance with the conclusive ultimate theoretical loadings determined by recommended calculation methods. The differences in the case of members with ultra-slender webs can be caused also by local transfer of loading in the top and bottom of these members. Obtained knowledge and results in this research allowed detailed analyses of real elastic-plastic interaction, overstrain and failure of thin and/or very thin webs and flanges off effective compression steel members.

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ON TIME-DEPENDENT RELIABILITY OF SUSTAINABLE STRUCTURES

Peculiarities of sustainable reliability predictions for load-carrying structures of buildings, construction and civil engineering works are discussed. The quantitative probabilistic parameters of the structural safety and durability of members and their systems are formulated and applied. A new strategy for probability-based quality predictions of sustainable structures is presented. The safety prediction is meant for particular members (sections, connections) exposed to action effects. Contrary to this prediction, the durability issues for whole structural members (slabs, beams, columns, walls) as auto-systems representing their multi-criteria failure mode are considered. The methods of conventional resistance and transformed conditional probability design in practical calculations of reliability parameters of sustainable structures and works are presented. It is recommended to calibrate the target reliability index of sustainable structures considering not only the consequences of failure of the members but also their functional working classes.

Introduction. Coating materials may effectively slow down steel or concrete corrosion and wood purefaction processes, but they cannot be acknowledged as everlasting protective measures for structures exposed to aggressive environmental conditions. Besides, these materials cannot preserve the structure form degradation due to mechanical injuries caused by wind storms, avalanches and earthquake motions. Therefore, the design on durability of structures is indispensable in up-to-date sustainable construction.

Irrational structural solutions and unexpected damages or accidents are categorically inadmissible for sustainable buildings. Dangerous failures may be caused not only by irresponsibility of designers and builders, but also due to the absence of perfectly and fully formulated recommendations and directions