Experimental Investigation of Compressed Thin-Walled Steel Members

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Abstract. 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. This continuous research joins on previous research of the first author of the paper. The aim of this research is to investigate and analyse the elastic-plastic post-critical behaviour of thin web and its interaction with flanges. The experimental program, test members and their geometrical parameters and material properties are evident from table 1 and table 2 as well as from figure 1 and figure 2. The test arrangement and failures of the test members are illustrated on Figures 3, 4 and 5. Some partial results are presented in Table 3 of the paper, too.

1. Introduction
The continued effort for economic design of steel structures lead to decrease their weight by shape and material optimization, 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 optimization 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 [1-4]. This paper presents basic information about 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. This research is distinctively oriented on the investigation and analyses of post-critical behaviour and interaction of slender/ultra-slender web with flanges in the process of their transformation and failure [1, 2, 5, 6].

2. The experimental program and tested 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 are illustrated in figure 1. Basic geometrical and material characteristics of several designed testing models/members are presented in table 2.
Table 1. The geometrical dimensions and materials of flanges and webs of testing models

| Testing models/members | Geometrical dimensions [mm] | Steel |
|------------------------|-----------------------------|-------|
|                        | Flanges         | webs          |
| M.G.  | C.G. | Marking | L | h | B | tf | D | tw |       |
| A     | 1    | AS11, AS12, AS13 | 250 | 112 | 60 | 100 |
|       | 2    | AS21, AS22, AS23 | 500 | 312 | 90 | 200 | 6 |      |
|       | 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 |
|       | 2    | BS21, BS22, BS23 | 500 | 212 | 90 | 200 | 6 |      |
|       | 3    | BS31, BS32, BS33 | 750 | 312 | 120 | 300 |
|       | 4    | BS41, BS42, BS43 | 1000 | 412 | 150 | 400 |

Figure 1. Scheme of testing models/members

Table 2. Basic geometrical and material characteristics of designed testing models/members

| Members    | Geometrical characteristics | Material characteristics |
|------------|-----------------------------|--------------------------|
|            |                            |                          |
| M.G.  | C.G. | λy = L / iy | λz = L / iz | βf = c / tf | βw = d / tw | γ = Aw / A | my = fyf / fyw |
| 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 |
|       | 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 and 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 steels S355 (flanges) and S235 (webs). The several cross-sectional groups have different dimensions, but the first of all have different web slenderness $\beta_w$. 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 $\beta_f$), 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 $\lambda_y, \lambda_z, \lambda_z > \lambda_0$). The ratio $\gamma$ 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 from 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.

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.

![Figure 2](image_url)

**Figure 2.** Characteristic strain-stress diagrams and determined material characteristics

Figure 2 shows the good quality of testing members’ material characteristics. Determined yield stresses of 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, the determined flanges yield stresses values were higher than the webs yield stresses, $f_{yf} > f_{yw}$. This means, that they are material combined ($m_1 = 1,054$, event. 1,143). In the case of materials group B it is categorical go about members with material combined cross-sections ($m_1 = 1,442$, event. 1,563). In the case of all testing bars a good material ductility was found, $A_5 > 29\%$. 
3. Methodology and test content
The tests have to bring out detailed investigation about transformation, failure and gross bearing capacity of the above-mentioned members, in consider of several designed geometrical and material parameters.

![Figure 3. General layout of the test, measurement of strains $\varepsilon$, deflections of the web $w$ and buckling $v$ of member BS41](image)

In accordance with research target, the emphasis is imposed on elastic-plastic post-critical behaviour 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 and 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. The strains $\varepsilon$ in the middle cross-section during consecutive programmed overloading of member was measured. Measurement was realized in 12 places, double-faced on the web in 6 places and also on the flanges in 6 places. The resistance tensiometers were used to measurement the strains $\varepsilon$ 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 $w$ was 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 was also investigated in the middle cross-section on the edges of flanges. The member’s global buckling $v$ was measured by means of mechanic gauges. General layout of the test, measurement of strains $\varepsilon$, lateral deflections of the web $w$ and global buckling $v$ are illustrated in figure 3.

The members during the test were consecutively overloaded and released. The member overloading was regulated close to its behaviour, measured values of strains $\varepsilon$ and deflections of the web $w$. The test continued up to total failure, defined by the beginning of consecutive, continuous increasing of strains $\varepsilon$ and deflections of the web $w$. Figure 4 illustrate the total failure of members AS22 a BS22 by local buckling of webs and flanges.
4. 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:

- $N_{el}$: 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,
- $N_{ul,el}$: ultimate elastic-plastic post-critical loading definite by attaining the ultimate strain $\varepsilon_u = \varepsilon_{yf}$ in the outer fibers of cross-sectional web,
- $N_{n,y}, N_{n,z}$: ultimate buckling loading of member according to axis $y$ and $z$ considering the elastic-plastic post-critical behaviour of the web.

Table 3 present the relevant values of several members’ ultimate loadings. All of members’ ultimate loadings were calculated according to real – measured dimensions and determined yield stresses of their flanges and webs. In general, ultimate $N_{n,z}$ 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.

In this time, all 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 $N_{n,exp}$ are also illustrated in table 3. Very good consonance can be found from the preliminary realized comparison between determined experimental bearing capacities $N_{n,exp}$ and theoretical ultimate loadings $N_{n,y}, N_{n,z}, N_{ul,el}$.

In the case of members with ultra-slender webs: $\beta = 200$, (AS41 ~ AS43 and BS41 ~ BS43) more significant differences was registered. Some of obtained experimental results and relations $N = w$ and $N = \varepsilon$ are illustrated in figures 5 and 6.

The comparing of theoretical and experimental capacities of members is presented in figure 7.
Table 3. Theoretical and experimental bearing capacities [kN]

| Member | $N_{el}$ | $N_{pl}$ | $N_{tot}$ | $N_{exp\,el}$ | $N_{u,z}$ | $N_{exp\,pl}$ | $N_{exp\,u,z}$ | $N_{exp\,u,y}$ |
|--------|----------|----------|-----------|---------------|----------|---------------|---------------|---------------|
| AS11   | 249.9    | 260.2    | 249.9     | 260.2         | 260.2    | 260.2         | 278.0         | 1.068         |
| 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     | 356.1         | 360.9    | 360.9         | 357.0         | 1.003         |
| AS22   | 377.1    | 415.6    | 321.9     | 354.3         | 359.2    | 359.2         | 373.0         | 1.053         |
| AS23   | 376.0    | 414.4    | 320.9     | 353.3         | 358.2    | 358.2         | 359.0         | 1.016         |
| AS31   | 540.2    | 560.3    | 424.5     | 435.6         | 444.8    | 444.8         | 447.0         | 1.026         |
| AS32   | 542.8    | 563.0    | 426.8     | 438.1         | 447.2    | 447.2         | 432.0         | 0.986         |
| AS33   | 549.7    | 570.0    | 432.2     | 443.4         | 452.7    | 452.7         | 442.0         | 0.997         |
| AS41   | 651.5    | 713.8    | 491.0     | 552.0         | 539.1    | 552.0         | 490.0         | 0.909         |
| AS42   | 653.9    | 716.6    | 493.9     | 555.4         | 542.0    | 555.4         | 512.5         | 0.946         |
| AS43   | 654.6    | 717.4    | 494.6     | 556.2         | 542.8    | 556.2         | 480.0         | 0.884         |
| BS11   | 253.6    | 339.8    | 253.6     | 335.5         | 339.8    | 339.8         | 357.0         | 1.064         |
| BS12   | 261.6    | 350.6    | 261.6     | 346.5         | 350.6    | 350.6         | 363.0         | 1.048         |
| BS13   | 257.0    | 345.1    | 257.0     | 341.0         | 345.1    | 345.1         | 357.0         | 1.047         |
| BS21   | 376.4    | 527.8    | 321.2     | 454.9         | 469.2    | 469.2         | 466.0         | 1.024         |
| BS22   | 376.0    | 527.3    | 320.9     | 454.7         | 468.7    | 468.7         | 492.0         | 1.082         |
| BS23   | 370.1    | 517.9    | 314.9     | 445.7         | 459.2    | 459.2         | 482.0         | 1.081         |
| BS31   | 544.6    | 711.3    | 429.2     | 569.9         | 592.8    | 565.0         | 565.0         | 0.991         |
| BS32   | 549.0    | 716.6    | 432.6     | 574.3         | 597.2    | 577.5         | 577.5         | 1.006         |
| BS33   | 546.1    | 713.5    | 430.7     | 572.2         | 595.0    | 562.5         | 562.5         | 0.983         |
| BS41   | 643.0    | 888.2    | 486.7     | 691.8         | 659.5    | 691.8         | 657.5         | 0.997         |
| BS42   | 654.7    | 902.1    | 494.4     | 709.2         | 676.1    | 709.2         | 590.0         | 0.873         |
| BS43   | 650.9    | 896.2    | 490.5     | 663.0         | 695.7    | 695.7         | 625.0         | 0.943         

Figure 5. Initial and final web buckling shapes of member AS31
5. Conclusions

- The results of presented research affirm and expand the knowledge of previous research about the elastic-plastic behaviour and bearing capacities of thin-walled compression members with quasi-homogenous and combined cross-sections.
- Elastic-plastic post-critical bearing capacity of compression members’ thin webs is on a large scale dependent on their initial buckling shape and also dependent on their forming shape during the loading process.
- Post-critical bearing capacity of compression members’ thin webs increases by increasing the number of buckling waves during the elastic-plastic and plastic stage of strain.
- Thin webs with slenderness $\beta \leq 150$ (A), event. $\beta \leq 100$ (B) prove a sufficient support of compression members’ flanges. Theoretical local bearing capacities $N_{u,\text{ep}}$ and total bearing capacities $N_{u,z}$ are in a good consonance with the obtained experimental bearing capacities $N_{u,\text{exp}}$. 

Figure 6. The web deflections $w$ in the middle and quarters of member BS 23 (a), the web and flanges strains $\varepsilon$ of member BS 22 (b)

Figure 7. The comparing of theoretical and experimental capacities of members, material group A (a), material group B (b)
In the case of members with webs’ slenderness \( \beta = 200 \), the influence of non-sufficient support of compression flanges by ultra-thin web was also manifested here. This effect was significant near the members’ ending, which can be caused by local transfer of loading to the flanges and web. In the case of these members, theoretical local bearing capacities \( N_{ul, ep} \) and total bearing capacities \( N_{ul, z} \) are a bit less than the experimental bearing capacities \( N_{ul, exp} \).

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