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Cover photo: Melbourne Central, old lead shot tower.

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Savings in weight by using CHS or SHS instead of angles in compressed struts and trusses

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ABSTRACT: The relationship between the cross-sectional area (A) and the radius of gyration (r) is determined for CHS, SHS and double-angle sections. The required A is calculated in function of compressive force N. The A - N diagram shows the weight savings achievable by using CHS or SHS instead of double-angle sections. An illustrative numerical example of a roof truss shows the significant differences among the volumes of trusses constructed from CHS, SHS and double-angle sections. The optimal slope of the upper chord giving the minimum volume of truss depends on the type of cross-section of compressed struts.

KEYWORDS: Compressed struts, tubular trusses, optimum design, weight savings, double-angle sections.

1 INTRODUCTION

Some authors dealing with the optimum design of trusses [e.g. Saka (1991), Koumousis (1992)] use the conventional rolled angle profiles. The aim of the present paper is to show the advantages of circular or square hollow sections (CHS or SHS) by calculating the weight savings in the case of compressed struts and trusses.

The main advantages of CHS or SHS over angle sections are as follows. 1) the overall buckling strength is higher. This is expressed e.g. in Eurocode 3 (1992) prescribing the buckling curve (b) for CHS and SHS and curve (c) for angles. 2) the radius of gyration (r) in function of the cross-sectional area (A) is much higher than that for double angle profiles. 3) the effective buckling length of chords and braces in trusses is smaller than that of angle profiles.

Trusses constructed from angles have several other disadvantages such as difficulties in manufacturing of nodes with gusset plates or the need of connecting the pairs of angles in prescribed distances. It should be noted that our investigations relate to trusses of larger roofs or smaller bridges and not to columns or towers in which single angle profiles can be advantageously used without gusset plates.

2 DESIGN OF CONCENTRICALLY COMPRESSED STRUTS

The radius of gyration (r) can be expressed by the cross-sectional area (A) as follows. For CHS and SHS this relationship can be exactly expressed using the local slenderness

$$\delta_C = D/t \text{ and } \delta_S = b/t$$

where D and b are the mean diameter and mean width, t is the thickness (Fig. 1). Limiting values for δ_C and δ_S are given for instance by Eurocode 3 (1992) for CHS

$$\delta_{CL} = 70 * 235 / f_y$$

where f_y is the yield stress, so for $f_y = 235$ and 355 MPa $\delta_{CL} = 70$ and 50, respectively. Note that, according to CIDECT (Wardenier et al. 1991), for both steel grades $\delta_{CL} = 50$ is given. For SHS, according to CIDECT (Packer et al. 1992),

$$\delta_{SL} = 1.25\sqrt{E / f_y}$$

thus, for steels of $f_y = 235$ and 355 MPa, $\delta_{SL} = 35$ and 30, resp. The formulae and values of a_C and a_S are summarized in Table 1.

For hot rolled equal leg double-angle sections an approximate a_d value can be obtained using r and A values of standard sections according to ISO 657-1 (1989) or DIN 1028 (1976). The calculations result in 0.6938 for single angles and

$$a_d = 0.6938 / \sqrt{2} = 0.49, \quad r = 0.49\sqrt{A}$$

Table 1. The radius of gyration expressed by cross-sectional area for CHS and SHS

	CHS	SHS
A	$\pi D^2 / \delta_C$	$4b^2 / \delta_S$
I_x	$\pi D^4 / (8\delta_C)$	$b^4 / (24\delta_S)$
$r = \sqrt{I_x / A} = a\sqrt{A}$	$a_C = \sqrt{\delta_C / (8\pi)}$	$a_S = \sqrt{\delta_S / 24}$
δ_L $(f_y = 235\ MPa)$	$\delta_{CL} = 70$	$\delta_{SL} = 35$
δ_L $(f_y = 355\ MPa)$	$\delta_{CL} = 50$	$\delta_{SL} = 30$
a $(f_y = 235\ MPa)$	$a_{CL} = 1.6689$	$a_{SL} = 1.2076$
a $(f_y = 355\ MPa)$	$a_{CL} = 1.4105$	$a_{SL} = 1.1180$

for double-angle profiles. It can be seen that a_d is much smaller than a_{CL} and a_{SL}.

In the optimum design of a concentrically compressed strut the cross-sectional area should be minimized considering the overall and local buckling constraints:

$$A \rightarrow \min.$$

The overall buckling constraint is defined according to the Eurocode 3 (1992) as follows.

$$N / A \leq \chi f_y; \quad 1/\chi = \phi + \sqrt{\phi^2 - \bar{\lambda}^2}$$

$$\bar{\lambda} = \lambda / \lambda_E = KL / (r\lambda_E); \quad \lambda_E = \pi\sqrt{E / f_y} \qquad (1)$$

$$\phi = 0.5\left[1 + \alpha\left(\bar{\lambda} - 0.2\right) + \bar{\lambda}^2\right]$$

where $\alpha = 0.34$ for CHS and SHS, $\alpha = 0.49$ for double angle sections. K is the end restraint factor, for double angles K = 1, for CHS and SHS in trusses, according to CIDECT (Rondal et al. 1992), for chords K = 0.9, for braces K = 0.75. For $E = 2.1*10^5$ MPa and $f_y = 235$ MPa $\lambda_E = 93.91$.

The local buckling constraint is

$$\delta \leq \delta_L \qquad (2)$$

Treating Eq. (2) as equality (active constraint) the two unknown sizes of CHS or SHS (D, t) or (b, t) can be calculated.

In the optimum design of tubular trusses these sizes should be treated separately, since the strength and geometric limitations for truss nodes rely on these unknowns (Farkas 1990). Instead of these sizes we use here the relationship $r = a\sqrt{A}$, since this method is suitable for angle sections.

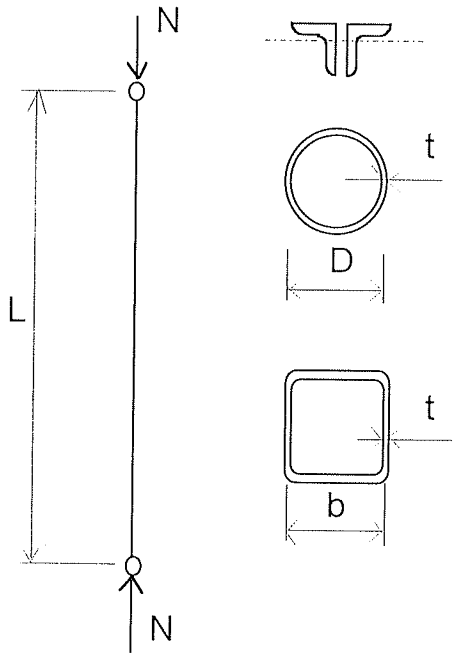

Fig.1 Compressed strut of CHS, SHS and double-angle section.

Using this relationship, A will be the sole unknown in the overall buckling constraint.

Introducing the symbols

$$c_o = 100K / \lambda_E, \quad x = 10^4 N / L^2, \quad y = 10^4 A / L^2$$

where L is the strut length in [mm], A in [mm^2], N is the compressive force in [N], Eq. (1) can be written as

$$\frac{x}{f_y} \leq \frac{y}{\phi + \sqrt{\phi^2 - \frac{c_o^2}{a^2 y}}} \qquad (3)$$

$$\phi = 0.5\left[1 + \alpha\left(\frac{c_o}{a\sqrt{y}} - 0.2\right) + \frac{c_o^2}{a^2 y}\right]$$

Unfortunately, it is impossible to solve Eq. (3) for y in closed form, therefore a computer method is used to calculate y for given x.

Fig.2 shows the relationships $10^4 N / L^2 - 10^4 A / L^2$ for CHS, SHS and double-angle sections in a double log coordinate system. In the case of CHS and SHS the end restraint factors K=0.9 and 0.75, for double angle sections K = 1 is considered, so these diagrams can be used for the design of various compression members in trusses.

It can be seen that the cross-sectional area of double-angle profiles is much greater than those of CHS and SHS. The difference or the savings in weight depends on N / L^2 -value or on the strut slenderness λ. The $s = \lambda$ -curve is also given for CHS in the case of K = 0.9. The higher the slenderness the larger the weight savings.

The ratio between the A / L^2 -values for double-angle sections and CHS K = 0.9 varies from 3.5 to 1.1 in the range of

$$10^4 N / L^2 = 25 - 10000 \, (\lambda = 114 - 8).$$

For SHS K = 0.9 this ratio varies from 2.7 to 1.1. These numbers illustrate the significant weight savings.

It should be noted that, for design purposes of CHS and SHS struts, the Japanese Road Association

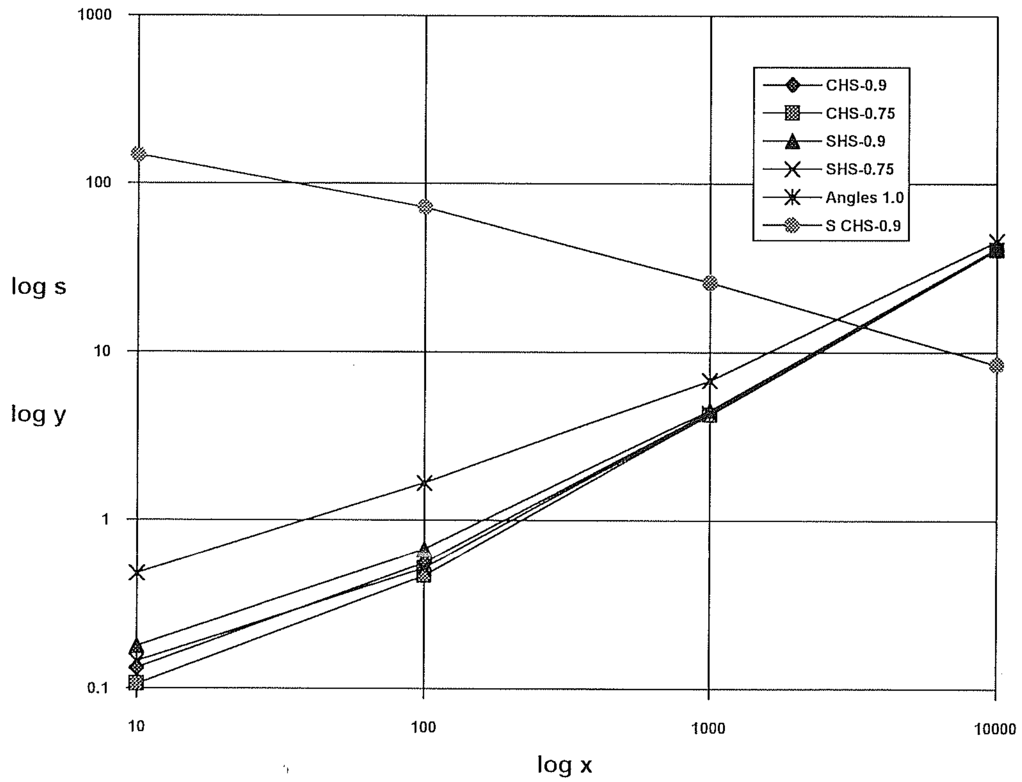

Fig.2. A - N diagram. Required $10^4 A / L^2$ values and slendernesses $s = \lambda = KL / r$ in function of $10^4 N / L^2$ in double-log coordinate system for CHS and SHS in the case of $K = 0.9$ and 0.75, resp. and for double-angle section for $K = 1$. Slendernesses are given only for CHS with $K = 0.9$. All values are calculated for yield stress $f_y = 235$ MPa

(JRA) overall buckling curve (Hasegawa et al. 1985) can be used instead of Eurocode 3 curve (b). In this case closed formulae can be given for cross-sectional sizes.

$$N / A \leq \chi f_y$$

$$\chi = 1 \qquad \text{for} \quad 0 \leq \bar{\lambda} \leq 0.2$$

$$\chi = 1.109 - 0.545\bar{\lambda} \quad \text{for} \quad 0.2 \leq \bar{\lambda} \leq 1 \tag{4}$$

$$\chi = \frac{1}{0.773 + \bar{\lambda}^2} \quad \text{for} \quad \bar{\lambda} \geq 1$$

Introducing the symbols

$$\vartheta_C = 100D / L \quad \text{and} \quad \vartheta_S = 100b / L$$

and using $\bar{\lambda} = c / \vartheta$ the closed formulae are as follows.

For $0.2\vartheta \leq c \leq \vartheta$

$$\vartheta = 0.24572c\left[1 + \sqrt{1 + \frac{14.93475\nu}{c^2}}\right] \tag{5.a}$$

and for $\vartheta \leq c$

$$\vartheta = \left\{0.3865\nu\left[1 + \sqrt{1 + \frac{6.69424c^2}{\nu}}\right]\right\}^{1/2} \tag{5.b}$$

for CHS $c_c = \frac{100K\sqrt{8}}{\lambda_E}, \quad \nu_{CL} = \frac{10^4 N}{L^2} \cdot \frac{\delta_{CL}}{\pi f_y}$

for SHS $c_S = \frac{100K\sqrt{6}}{\lambda_E}; \quad \nu_{SL} = \frac{10^4 N}{L^2} \cdot \frac{\delta_{SL}}{4 f_y}$

3 NUMERICAL EXAMPLE OF A TRUSS

The design method described in Section 2 is applied for compression members of a statically determinate roof truss with non-parallel chords to illustrate the savings in weight in the case of trusses by using CHS or SHS instead of double-angle sections.

Consider the truss shown in Fig.3. Four different cross-sections (1-4) are designed for each case. To find the optimal truss height (h) or the optimal slope angle of the upper chord, the truss is designed for heights h=2.5, 3.5, 4.5, 6.0 and 7.5 m (corresponding slope angles are

$$4.76°, 9.46°, 14.04°, 20.56° \text{ and } 26.56°).$$

In the design of CHS and SHS struts, ection properties of the ISO/DIS 4019.2 as well as the tables given by Dutta and Würker (1988) (DIN 2448, DIN 2458, DIN 59411) have been used. The results of the calculations are summarized in Table 2 and Fig.4.

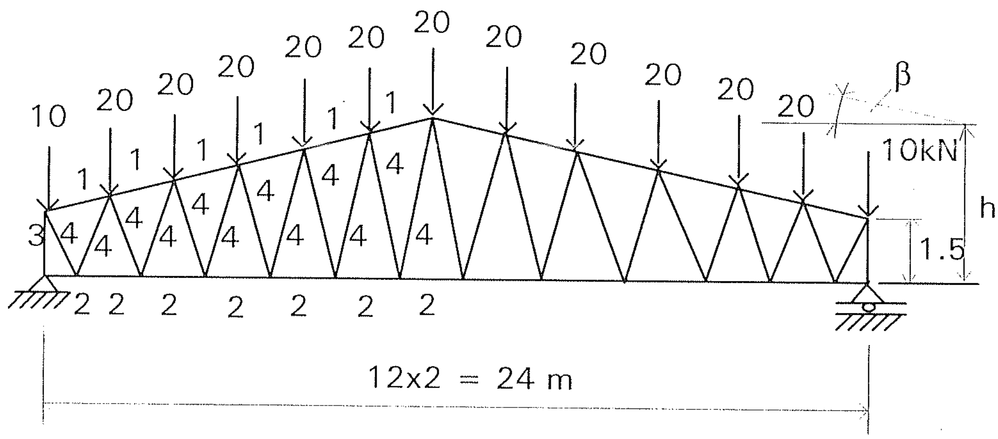

Fig.3 Numerical example of a roof truss. 1 - section for upper chord, 2 - section for lower chord, 3 - section for outside columns, 4 - section for braces. The height h varies with the slope angle β of the upper chord.

Table 2. Total volumes of trusses of various heights

Height h (m)	Slope angle β^o	Section	Upper chord 1	Lower chord 2	Outside columns 3	Braces 4	Total volume 10^{-7} (mm^3)
		CHS	152.4/2.9	133/3.2	108/2.3	108/2.3	10.72
2.5	4.76	SHS	115/3.2	110/3	70/3.2	70/3.2	11.04
		angles	2x80x8	2x50x7	2x50x6	2x70x6	18.14
		CHS	152.4/2.3	139.7/2.3	101.6/2	101.6/2	9.24
3.5	9.46	SHS	115/2.6	80/3.2	70/2.6	70/2.6	9.71
		angles	2x70x7	2x50x5	2x50x6	2x55x6	15.36
		CHS	139.7/2	127/2	101.6/2	101.6/2	8.95
4.5	14.04	SHS	90/3	80/2.6	70/2.6	70/2.6	9.80
		angles	2x65x7	2x45x5	2x50x6	2x60x6	17.18
		CHS	127/2	101.6/2	101.6/2	88.9/2	8.79
6.0	20.56	SHS	90/2.6	90/2	70/2.6	70/2.6	10.45
		angles	2x70x6	2x40x4	2x50x6	2x60x6	18.87
7.5	26.56	CHS	114.3/2	88.9/2.3	101.6/2	88.9/1.8	8.84

It can be seen that the optimal truss height (slope angle) giving the minimal total volume of the structure depends on the cross-sectional shape. In the investigated numerical example the optimal slope angles are as follows:

for double-angle sections

$\beta \cong 10^\circ$, for SHS $\cong 12^\circ$ and for CHS $\cong 20^\circ$.

It should be mentioned that the volumes are calculated with discrete available sections, therefore some differences are between calculated values and the continuous curves shown in Fig.4, mainly in the case of double-angle sections.

The savings in weight by using CHS or SHS instead of double-angle sections, according to Table 2, are 41-53 % or 39-45 %, respectively

e.g. 100 (18.14 - 10.72 / 18.14) = 41 % etc.

These differences are more than the difference between the material costs of CHS, SHS and rolled angles, thus material cost savings can also be achieved.

Note that the sensitivity of the volume functions for CHS and SHS is relatively small, but the difference between the volumes for the heights h = 2.5 and the optimal h_{opt} = 6 m (for CHS) is

100 (10.72 - 8.79 / 10.72) = 18 %,

so, for economic design, it is important to choose the optimal truss slope.

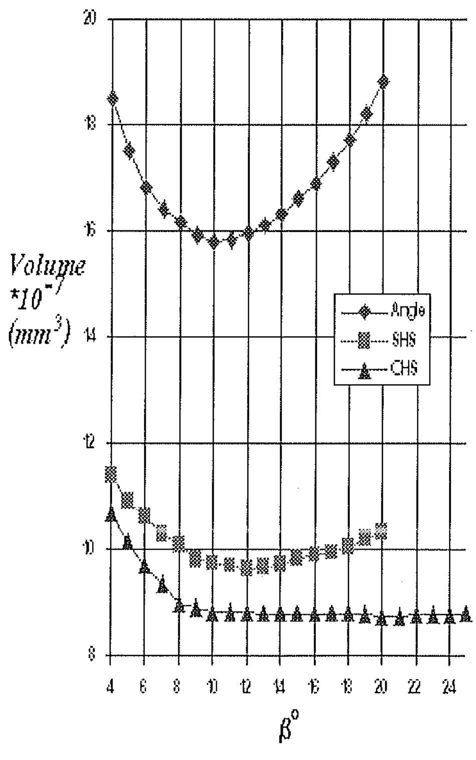

Fig.4 The total volume of trusses as a function of the slope angle (β°) of the upper chord.

4 CONCLUSIONS

The overall buckling strength of concentrically compressed CHS and SHS struts is much larger than that of double-angle section struts, therefore significant savings in weight and material cost can be achieved by using CHS and SHS instead of double-angle sections in compressed struts and trusses.

By using the limiting local slendernesses and the relationships between the radius of gyration and cross-sectional area, design diagrams are given for the calculation of the required cross-sectional area in function of the compressive force and strut length.

The illustrative numerical example of a roof truss, constructed from CHS, SHS or double-angle sections shows that the optimal geometry of the truss depends on the cross-sectional shape of compression members. This conclusion is important, since this aspect has not been pointed out till now in the optimum design of trusses.

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