NEW DESIGN TOOLS FOR STRUCTURAL HOLLOW SECTIONS OF STAINLESS STEEL

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Abstract

Previously stainless steel has been used in buildings as facades, envelopes, canopies, roofing and water drainage systems mainly for aesthetic reasons. The design standards and manuals for stainless steel structural members and connections in Europe have been developed since the beginning of the 1990's. Those standards and manuals give recommendations on how to select the most appropriate grade of stainless steel for a given application and provide information on the mechanical properties, physical properties and design strength. Until recently, in many applications stainless steel structural hollow sections were taking a share as structural elements covering square, rectangular and circular cross-sections. Therefore, research has been conducted on members and welded connections in hollow sections by testing structural resistances at room temperature and in fire situations.

In this paper new design tools are presented in order to help designers to utilise stainless steel structural hollow sections. Information in this field developed in Europe, Australia and North America by different R&D projects was included in the Design Handbook. This Design Handbook covers aspects of material behaviour, cross-section design, member design, connections, fire resistant design, fabrication and design examples. The Design Handbook gives profound information and recommendations for designers who already are familiar with carbon steel structural hollow sections.

In addition, the software WinRami Stainless was developed and modified to include structural calculation of stainless steel structural hollow sections. WinRami Stainless is the FE-based structural design software, which includes the resistance calculation based on the standard EN 1993-1-4: Eurocode 3- Design of steel structures – Part 1-4: General rules – Supplementary rules for stainless steels[1] and the standard EN 1993-1-2 Eurocode 3: Design of steel structures - Part 1-2: General rules - Structural fire design[2]. Materials included are the austenitic grades given in the Annex C of EN 1993-1-2 and in Table 7.1 of the Third Edition of the Design Manual for Structural Stainless Steel [5]. The material models used are based on Eurocode 3. Structural design with WinRami Stainless software utilizes two strength classes for structural hollow sections: annealed condition stainless steel grades and cold worked grade CP 350 and C700. For fire resistant design the reduction factors calculating strength and elastic modulus at specific temperature are given according to EN1993-1-2. WinRami Stainless is used for solving 2D structures consisting of frames and trusses.

Introduction

Stainless steel structural hollow sections have great potential in structural applications in all the branches of industry. These profiles are very well known and used in industrial applications in which good corrosion resistance is needed. Many research projects has been performed to determine the resistance of columns, beams and joints exploiting the enhancement in mechanical strength as a result of cold-working. The structural testing results of RFCS-funded research projects of stainless steels [3,4] are included in Eurocode standards. The structural hollow sections have also been studied outside Europe since the beginning of the 1990's [9,10,11]. The enhanced strength of cold-worked hollow sections of austenitic grades has been studied for a yield strength of appr. 450 N/mm^2 in welded structures [6,12,13,14]. The Steel Construction Institute (SCI) has developed software[3,4] suitable for calculating the resistance of a single member based on EN1993-1-4. The latest results of RFCS projects were published by SCI and Euro-Inox in the Third Edition of the - Design Manual for Structural Stainless Steel, published in 2006[5].

This paper is focused on mechanical strength of stainless steel hollow sections, though many other items are also discussed in the Design Handbook for structural hollow sections of stainless steel. The main differences from structural steel properties are the strong ability for strain hardening within the austenitic grades, high mechanical strength at short term higher temperatures and corrosion resistance. The Design Handbook for structural hollow sections of stainless steel and WinRami Stainless have been developed based on the standard EN 1993-1-4, Finnish national annex NA and related standards EN 1993-1-1, EN 1993-1-8 and EN 1993-1-2. The material selection from a corrosion point of view is shown according to EN 1993-1-4 and the Material Handbook [15] (in Finnish).

Design Handbook for structural hollow sections of stainless steel

The Design Handbook follows the recommendations for structural design with hollow sections given by EN 1993-1-4. The standard EN 1993-1-4 allows the strength to be utilised up to a yield strength value of 480 N/mm^2. EN 1993-1-4 ANNEX B B.2 (2) says "The design rules given in this Part 1-4 are applicable for materials up to grade C700 and CP350".
Austenitic grades (1.4301, 1.4401/1.4404, 1.4541 and 1.4571) and ferritic grades (1.4003, 1.4509 and 1.4521) in the annealed condition have a yield strength between 220 - 320 N/mm^2 (exception austenitic grades 1.4318 and 1.4372, f_y = 350 N/mm^2). The yield strength enhanced by cold-working is allowed to be used as nominal yield strength in context with austenitic grades. The nominal strength of cold-formed hollow sections is classified to a strength class of CP350 and C700. It is possible to utilise a higher strength class than CP350 and C700 for cold-formed hollow sections with the procedure given in EN 1993-1-4. The duplex-grades 1.4462 and 1.4162 have a yield strength value of 480 N/mm^2 which is used as nominal yield strength.

The Design Manual [5] allows the strength achieved by cold-working to be utilised at maximum CP500. In addition, in the guidance on fire resistance the Design Manual presents a less conservative approach than EN 1993-1-4.

The austenitic stainless steel grades have high mechanical strength values for a short period at high temperatures. The yield strength and modulus of elasticity sustains their values well up to temperatures of 800 ^{0}C. Figure 1 shows the value of effective yield strength for fire design with three different austenitic stainless steel grades.

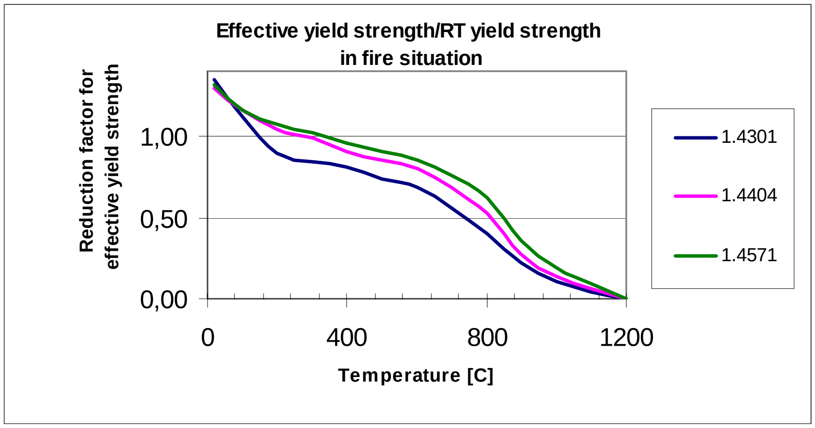

Figure 1. Reduction factors as a function of temperature for effective yield strength of austenitic grades 1.4301, 1.4404 and 1.4571.

The effective yield strength $f_{y,\theta}$ is calculated using the formula given below (EN 1993-1-2):

$$f_{y,\theta} = f_{0,2p,\theta} + k_{2\%,\theta}(f_{u,\theta} - f_{0,2p,\theta}) \quad (1)$$

The parameter values for formula (1) are given by standard EN1993-1-2. The Design Manual [5] gives the parameter values for the materials in strength class CP500.

Table 1. Stainless steel grades used as hollow section material.

	Steel	Typical chemical alloying, %						$R_{p0,2}$ [N/mm^2]	R_m [N/mm^2]	A_5 [%]	KV [J]
	EN [1)]	C	N	Cr	Ni	Mo	Muut	RT	RT	RT	RT
Ferritic stainless steel	**1.4003**	0,02	-	11,2	0,5	-	-	320	450	20	-
	1.4509	0,02	-	18,0	-	-	Ti+Nb	250	430	18	-
	1.4512	0,03	-	11	-	-	Ti	220	380	25	-
	1.4521	0,02	-	18	-	2	Ti+Nb	320	420	20	-
Duplex- stainless steel	1.4162	0,03	0,22	21,5	1,5	0,3	5Mn	450	650	30	60
	1.4362	0,02	0,10	23	4,8	0,3	-	400	630	25	60
	1.4462	0,02	0,17	22	5,7	3,1	-	460	640	25	60
	1.4410	0,02	0,27	25	7	4	-	530	730	20	60
CrNi- ja CrMn- stainless steel	**1.4318**	0,02	0,14	17,7	6,5	-	-	350	650	40	60
	1.4372	0,05	0,15	17	5	-	6,5Mn	330	750	40	60
	1.4301	0,04	-	18,1	8,3	-	-	210	520	45	60
	1.4307	0,02	-	18,1	8,3	-	-	200	500	45	60
	1.4311	0,02	0,14	18,5	10,5	-	-	270	550	40	60
	1.4541	0,04	-	17,3	9,1	-	Ti	200	500	40	60
	1.4306	0,02	-	18,2	10,1	-	-	200	500	45	60
CrNiMo –stainless steel	**1.4401**	0,04	-	17,2	10,2	2,1	-	220	520	45	60
	1.4404	0,02	-	17,2	10,1	2,1	-	220	520	45	60
	1.4436	0,04	-	16,9	10,7	2,6	-	220	530	40	60
	1.4432	0,02	-	16,9	10,7	2,6	-	220	520	45	60
	1.4406	0,02	0,14	17,2	10,3	2,1	-	280	580	40	60
	1.4571	0,04	-	16,8	10,9	2,1	Ti	220	520	40	60
	1.4435	0,02	-	17,3	12,6	2,6	-	220	520	45	60
	1.4539	0,01	-	20	25	4,3	1,5Cu	220	520	35	60
	1.4529	0,02	0,2	20	25	6,5	0,5Cu	300	650	40	60
	1.4547	0,01	0,2	20	18	6,1	Cu	300	650	40	60
	1.4565	0,02	0,45	24	17	4,5	5,5Mn	420	800	30	90

[1)] Stainless steels with bold marking are included in EN 1993-1-4.

The Design Handbook presents the mechanical properties of hollow sections, Table 1, in structural applications highlighting the different stainless steel grades and their alloying from the point of view of corrosion properties, material choice for given boundary conditions and handling as well as fabrication in workshops. Information given in the Design Handbook covers widely used austenitic and duplex stainless steel grades. Ferritic-, austenitic CrMn- and lean-duplex grades are also included.

WinRami Stainless

The WinRami software has been developed for the strength calculation of lattice truss and frame structures made of structural hollow sections or welded I-profiles. The software is capable of solving displacement, member forces and support reactions of a structure. The structural analysis is based on FE-calculation. Loading can act as in-plane load and the structural analysis done is 2D-analysis. The resistance analysis is capable of taking care of buckling of members both in-plane and out-of-plane directions. Initially the WinRami software was developed by Rautaruukki Oyj for carbon steel structural hollow sections and the resistance analysis for stainless steel structures has been added to the software later.

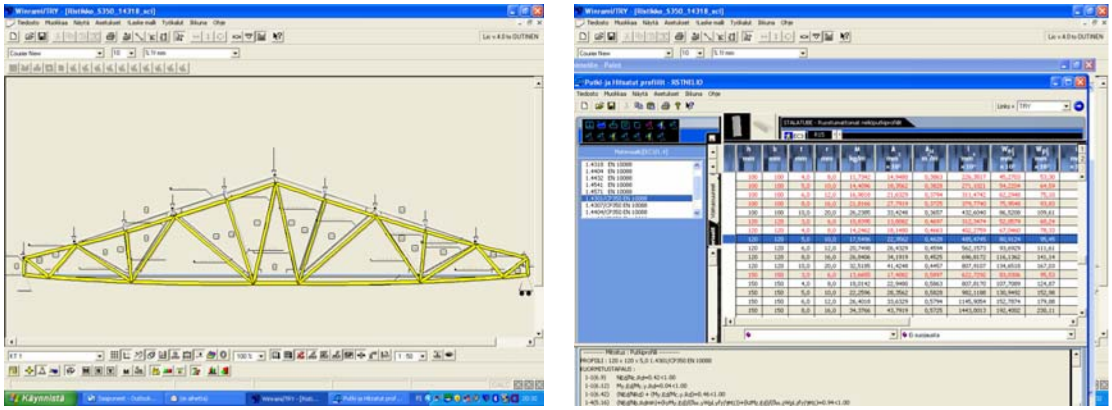

Figure 2. A schematic view of WinRami stainless resistance analysis.

The resistance analysis is based on the chosen design code for structural hollow sections of rectangular, square and circular cross section. The design code for stainless steel structural hollow sections is based on EN1993-1-4 and Finnish national annex, which refers to EN 1993-1-1, EN1993-1-2 and EN1993-1-8. The Winrami software includes the programs PROFILE, LIICONT and MOMCONT. The PROFILE is capable of solving a single member resistance. LIICON and MOMCON are programs solving the lattice girder joints and beam-to-column joints.

Main differences from structural steel hollow section resistance analysis are the values of partial factors, strength classification of cold-worked material, buckling curve, interaction of bending moment-normal force, and material mechanical strength at fire temperatures. The main differences are explained below.

The partial factors used by WinRami Stainless are recommended values according to EN 1993-1-4.

Winrami-stainless includes the structural and resistance analysis at room temperature and at fire situation temperatures for austenitic materials 1.4301, 1.4307, 1.4318, 1.4404, 1.4432, 1.4541 and 1.4571. Austenitic grades were chosen because of their good availability in a wide dimension range as structural square-, rectangular- and circular hollow sections. The maximum nominal design strength value in software for austenitic grades of cold-worked hollow sections is 350 N/mm^2 which conforms to strength class C350 and C700.

The buckling curve for stainless steel hollow sections is different from structural steel one by the value of limiting slenderness (0,2 to 0,4 stainless steel) and by the value of the modulus of elasticity E (210000N/mm^2 to 200 000 N/mm^2 stainless steel). The buckling curve “c” is used for stainless steel cold formed hollow sections.

Interaction normal force-bending moment at room temperature design differs from that of structural steels when calculating the interaction factors k_y and k_z. WinRami stainless uses the recommended formulae for determining the value for interaction factors.
When the loading is axial compression and uniaxial major axis moment the failure mode is buckling about the major axis:

$$\frac{N_{\mathrm{Ed}}}{(N_{\mathrm{b,Rd}})_{\min}} + k_y \left(\frac{M_{\mathrm{y,Ed}} + N_{\mathrm{Ed}}\, e_{\mathrm{Ny}}}{\beta_{\mathrm{W,y}} W_{\mathrm{pl,y}}\, f_{\mathrm{y}} / \gamma_{\mathrm{M1}}} \right) \le 1 \qquad (2a)$$

When the loading is axial compression and uniaxial minor axis moment the failure mode is buckling about the minor axis:

$$\frac{N_{\mathrm{Ed}}}{(N_{\mathrm{b,Rd}})_{\min}} + k_z\left(\frac{M_{\mathrm{z,Ed}} + N_{\mathrm{Ed}}\, e_{\mathrm{Nz}}}{\beta_{\mathrm{W,z}} W_{\mathrm{pl,z}}\, f_{\mathrm{y}} / \gamma_{\mathrm{M1}}}\right) \leq 1 \qquad (2b)$$

The interaction factors are calculated as follows:

$$k_y = 1{,}0 + 2\left(\bar{\lambda}_y - 0{,}5\right)\frac{N_{Ed}}{N_{b,Rd,y}}\ \text{, but}\ 1{,}2 \leq k_y \leq 1{,}2 + 2\frac{N_{Ed}}{N_{b,Rd,y}} \qquad (2.1)$$

$$k_z = 1{,}0 + 2\left(\bar{\lambda}_z - 0{,}5\right)\frac{N_{Ed}}{\left(N_{b,Rd}\right)_{\min 1}}\ \text{, but}\ 1{,}2 \leq k_z \leq 1{,}2 + 2\frac{N_{Ed}}{\left(N_{b,Rd}\right)_{\min 1}} \qquad (2.2)$$

Lattice girder joints are calculated according to ENV 1993-1-8. The calculation includes checking of the geometry of joints and structural resistance of joints. This means tens of formulae to be checked, Table 3. The yield strength of the profiles is restricted to a maximum of 460 N/mm^2 by ENV 1993-1-8. WinRami stainless includes materials whose maximum yield strength is limited to 350 N/mm^2. The typical stainless materials which reach 460 N/mm^2 are duplex- and cold-worked (CP500) austenitic grades, but are excluded from existing the WinRami stainless version in the current situation.

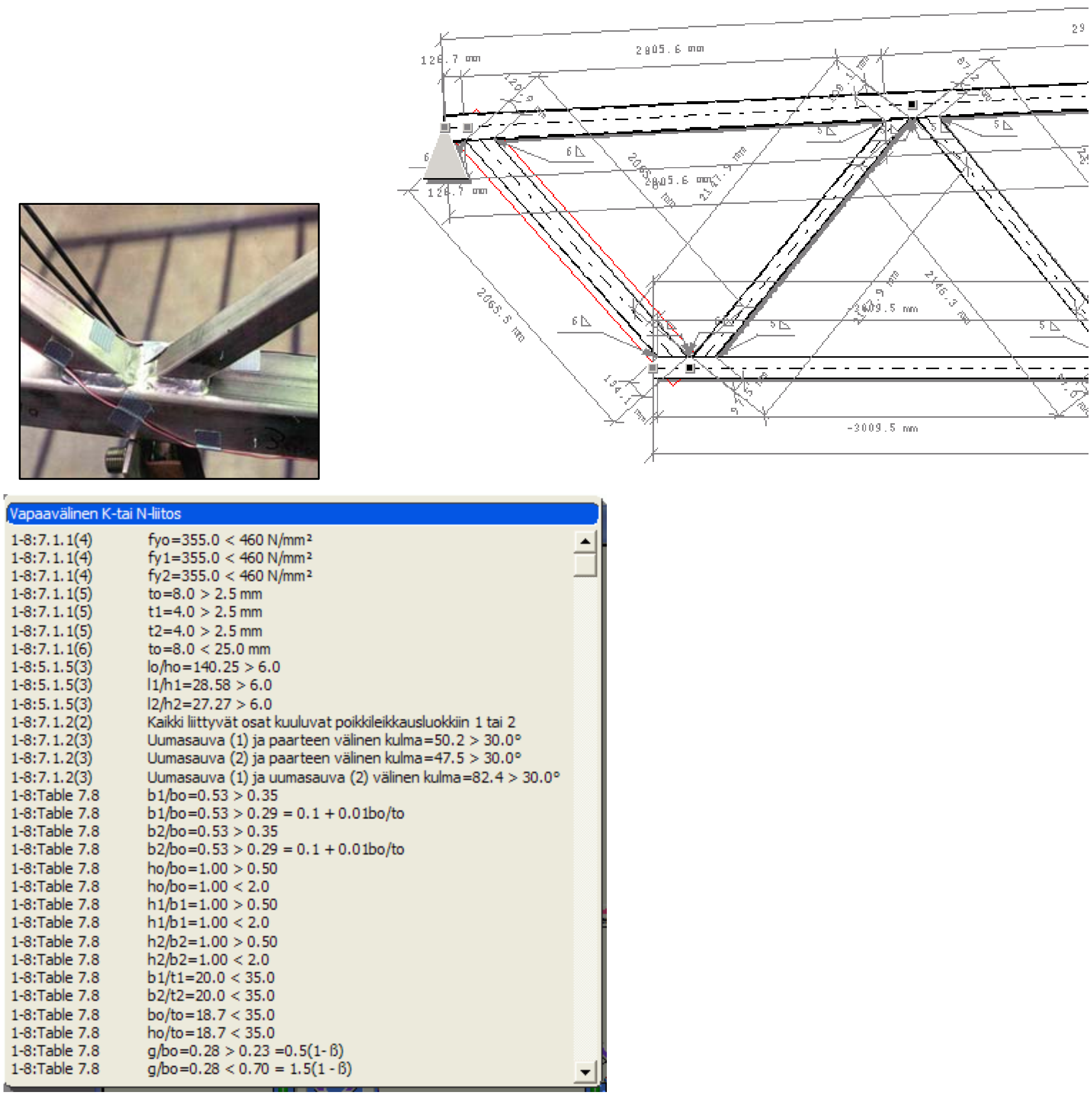

Figure 3. View of WinRami stainless joint calculation.

The calculation of the temperature rise of stainless steel differs slightly from that of carbon steel. The parameters are given by EN 1993-1-2. The emission factor value used is 0.4. WinRami stainless has an option to use a value of 0,2 [7,8].

Conclusions

New design tools to utilise stainless steel structural hollow sections in applications have been summarised including the Design Handbook and the software WinRami Stainless. The Design Handbook includes information about material grades, corrosion resistance, mechanical strength, structural resistance and work shop fabrication. The Design Handbook is targeted for detailed information about structural hollow sections of stainless steel. The WinRami Stainless is structural calculation software for truss and frame structures made of stainless steel. The WinRami Stainless is capable of solving the structural resistance of a structure based on EN1993-1-4 and related standards at room temperature and a fire situation. The Winrami Stainless software is targeted for the daily use of structural engineers.

Further development of design tools

The Design Handbook for structural stainless steel of hollow sections should be targeted to publish material information for structural purposes; such as material properties, design rules and design details. The Design Handbook shall be developed and dated parallel with design code development and practises in daily engineering work.

The further development of WinRami Stainless should be targeted to follow the changes in design codes and include the changes into the software. The other target is to include other suitable stainless steel grades like duplex-, lean duplex-, ferritic- and CrMn grades into software.

Acknowledgment

The new design tools for structural hollow sections of stainless steel presented in this paper have been generated as a result of the projects in cooperation with Stalatube Oy, Outokumpu Stainless Tubular Products (OSTP), the Finnish Constructional Steelwork Association (FCSA) and Outokumpu Tornio Works.

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