International Specialty Conference on Cold-Formed Steel Structures

(2006) - 18th International Specialty Conference on Cold-Formed Steel Structures

Oct 26th, 12:00 AM

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Eighteenth International Specialty Conference on Cold-Formed Steel Structures
Orlando, Florida, U.S.A, October 26 & 27, 2006

Parameter Study for First-Generation Sheeting Failure using a Theoretical and FE Model

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Abstract

First-generation sheeting is sheeting without longitudinal and transversal stiffeners. For the prediction of failure of this sheeting type, if loaded by concentrated load and bending moment, several theoretical models and design codes exist. One of these theoretical models was developed recently and predicts failure by using a derivative of the web-crippling deformation due to the concentrated load as an imperfection for the compressed flange for which the behaviour is predicted by Marguerre's simultaneous differential plate equations. The quality of the model has been checked with a whole range of experiments, however, the experiments did not have such a variation of variables that the model could be checked systematically. In this paper, a FE model is used to predict failure for a systematic variation of sheeting variables and the failure loads are used to check the theoretical model. For varying web width, angle between web and flange, corner radius, yield strength, plate thickness, and span length, the theoretical model performs well, qualitatively and quantitatively, compared to the finite element model. For the compressed flange width and load bearing plate width, the theoretical model results show some divergence from the FE model results, although absolute differences remain acceptable.

1 Introduction

For first-generation sheeting under combined bending and concentrated load, only a few theoretical models exist. It was already recognised in the seventies that curve-fitting rules could possibly be improved by using a fully theoretical model.

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As such, Tomà developed the RSD-model [Toma74a] that was based on the theoretical prediction of web buckling under bending and several other load types. In the meantime, Reinsch developed a model specifically for predicting moment redistribution and this model was based on an empirically determined capacity for concentrated load and energy equilibrium [Rein83a]. The second attempt for a model to substitute the design rules was by Bakker in 1992 [Bakk92a]. Bakker developed a fully analytical yield line model for short span members. However, by using yield line theory the model was complex to use and it could only be applied to short-span members with a specific failure mechanism. In this context it is good to note that promising attempts to use yield theory for theoretical models are still in progress [Hiri05a]. In 2000, a new theoretical model was developed for normal span members [Hofm01a], based on theories by Marguerre [Marg38a] and Vaessen [Bakk99a]. It proved to yield good results given the considered set of experiments [Hofm01a]. Furthermore, the model has the potential to be used for design rules, if the nonlinear behaviour of the compressed flange can be modelled by a simple yet accurate set of equations for initial imperfections (stress-less imperfections) [Bakk06a] and imperfections caused by a lateral load (stressed imperfections) [Bakk06b].

In this paper the theoretical model is systematically verified by using the finite element method. The finite element model that is used in this paper was developed by recognising the effort worldwide to develop such models [Sant86a, Wise91a, Talj92, Land94a, Bakk99a, Schaf97a, Davi97a, Sama99a, Kait04a]. Most of these models use a quarter model instead of a half or full model and they model the corner radius with only one element. More recently, more advanced models are developed [Akha04a] and it is realised that the corner should be modelled with more than one element for a wide scope of applications, for instance impact analysis [Lang06a].

2 Theoretical model

Experimental research indicates [Hofm01a] that the first signs of failure for sheeting under combined bending and concentrated load are little folds adjacent to the load bearing plate. The theoretical model focuses on predicting the load *F* at which these folds occur. It is assumed that the little folds occur if a point at the fold location yields.

Figure 1 shows a part of the sheeting's compressed flange and the load bearing plate. The location at which yielding occurs first is point Q. The principle of the model can be described as follows. A certain load *F* is assumed to work on the load bearing plate. Due to this load, a part of the compressed flange will deform. This deformation is modelled as shown in figure 1 by the curved lines in the shaded rectangle. A modification of the beam on elastic foundation method developed by Vaessen [Bakk99a] can be used to predict the change of distances d_Q and d_P. The difference between these two changes is the out-of-plane displacement w_P of point P:

$$w_P = d_P - d_Q \tag{1}$$

Assuming a sinusoidal displacement shape and using simple geometry, the out-of-plane displacement w_R of point R can be determined:

$$w_P = w_R \cos\left(\frac{\pi}{b}\left(\frac{1}{4}b\right)\right) \Leftrightarrow w_R = \left(\sqrt{2}\right)w_P \tag{2}$$

Because of load F, a bending moment acts in the section and therefore, a compression force F_{tf} is present in the compressed flange longitudinal direction. This compression force F_{tf} results in a compression stress σ_z at the shaded rectangle. A solution of Marguerre's equations [Marg38a], makes it possible to predict the Von Misses stress at point Q (at the outer fibre) for a given out-of-plane displacement w_R of point R and compression stress σ_z.

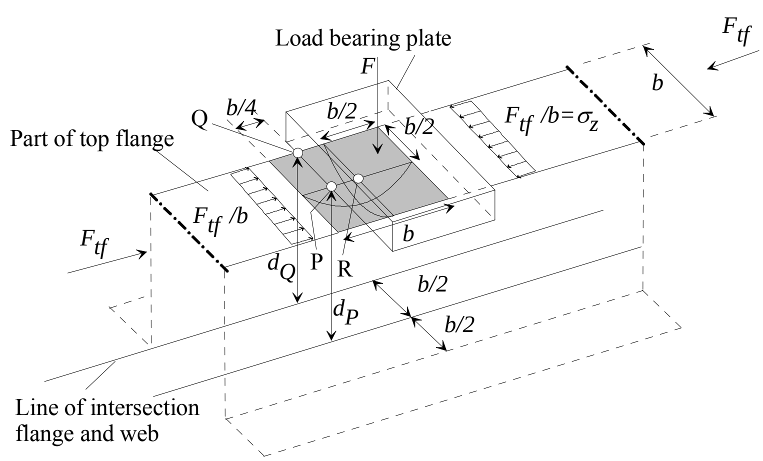

Figure 1, a part of the sheeting's compressed flange

Using a bisection iteration method, the specific load F at the load bearing plate can be found, needed to reach the yield stress at point Q. This load F is the predicted ultimate load of the sheeting. Note that in the model, local indentation of the section, compression stresses in the compressed flange, and non-linear behaviour of the compressed flange are all taken into account.

The model assumes that the out-of-plane displacement w_R does not imply the occurrence of stresses in the compressed flange. However, because the out-of-plane displacement is caused by the concentrated load, stresses exist. This is currently under investigation [Bakk06b]. Furthermore, the model uses a location of first yield at the location where first plastic behaviour is seen for the experiments. However, plate theory may indicate that first yield occurs at another location in the plate. More information and the comparison of the model with experiments can be found in [Hofm01a].

3 FE model

A finite element model as presented in [Klei06a] was used. The FE model is built with Ansys 8.1 using solid modelling. This means the geometry of the sheet-section is primarily generated via keypoints, lines, and areas. A half sheet-section is modelled because symmetry is valid for the cross-section but not in length direction for specific failure mechanisms. For the application of imperfections, the geometry is split up in parts in length direction for which the sheeting height can be adjusted to fit the imperfections required. For the sheet-section shell elements "SHELL43" are used. They have four nodes (with 6 degrees of freedom each) and extra displacement shapes. The elements are capable of describing plasticity, large deflections, and large strains and there are five integration points along the thickness. The material behaviour of the shell elements is specified using points of the real stress-strain curve of steel tension tests. Element sizes are listed in table 1.

Table 1, element sizes for finely and coarsely meshed parts

	Finely meshed part		Coarsely meshed part	
	Longitudinal dir.	Transverse dir.	Longitudinal dir.	Transverse dir.
Bottom flange	4 mm	4 mm	24 mm	24 mm
Bottom corner	5 mm	3 elements	18 mm	1 element
Web	10 mm	10 mm	24 mm	24 mm
Top corner	5 mm	3 elements	18 mm	1 element
Top flange	10 mm	10 mm	24 mm	24 mm

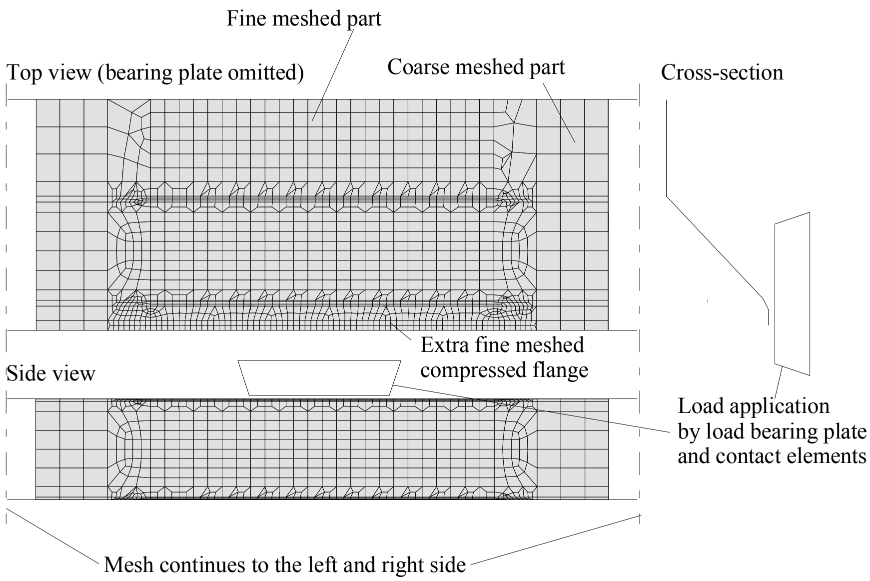

Figure 2, finite element model

The load bearing plate is made of a single solid element "SOLID45". It is wedge shaped to avoid contact difficulties near the bearing plate edge, see also figure 2. The three sides facing to the sheet-section are covered with "TARGE170" target elements. Sheet-section nodes that possibly contact these elements are provided with contact elements "CONTA175".

Along the longitudinal section line, boundary conditions are applied to assure symmetry conditions. Supports are made by boundary conditions at two lines near the ends of the bottom flange.

Loading is applied via prescribed displacements for the load bearing plate. A Newton-Rhapson solution strategy is used for which calculations were forced to continue if no convergence could be accomplished.

4 Parameter study

The theoretical model as presented in section 2 was already verified with several sets of experiments [Hofm01a], also from other researchers. These sets were quite large and in total the model was checked against 383 experiments. However, even with 383 experiments it is not possible to find -for all section variables- combinations of experiments that differ for just one variable along the total relevant range of that variable. Therefore the finite element model as presented in section 3 was used to carry out a parameter study as shown in table 2. Variables are explained in the table and figure 3.

Table 2, parameter study

		Change of variable in order to generate simulation value (simulation)		Default values (also relevant for simulation A) ↓	Change of variable in order to generate simulation value (simulation)
		much smaller -- ←	smaller - ←	default	larger → +
b_w	web width [mm]	-	75 (B)	100	125 (C)
b_{bf}	flange width [mm]	-	40 (D)	70	100 (E)
θ_w	angle web-flange [deg.]	-	50 (F)	70	90 (G)
r_{bf}	corner radius [mm]	1(H)	3 (I)	5	10 (J)
f_y	yield strength [N/mm2]	-	300 (K)	355	400 (L)
t	plate thickness [mm]	-	0.5 (M)	0.68	1 (N)
L_{span}	span length [mm]	-	1400 (O)	1800	2400 (P)
L_{lb}	plate width [mm]	-	50 (Q)	100	150 (R)

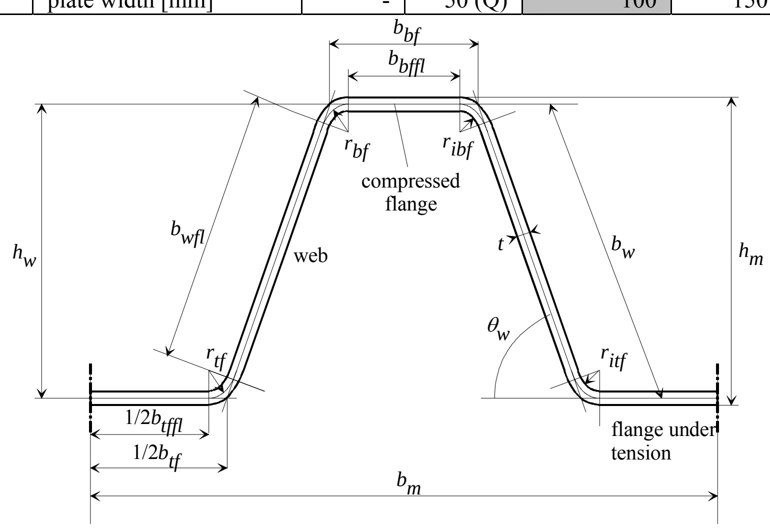

Figure 3, sheeting variables

Simulation "A" as listed in table 2 uses all default variable values as listed in the column below. Simulation "B" equals simulation "A" for all variable values except the web width which equals 75 instead of 100 mm in this case. Like simulation "B", the other simulations differ only for one variable to simulation "A" as indicated in table 2.

Web width
Figure 4 shows the ultimate load as predicted by the theoretical model (section 2) and the finite element model (section 3) for a variable web width.

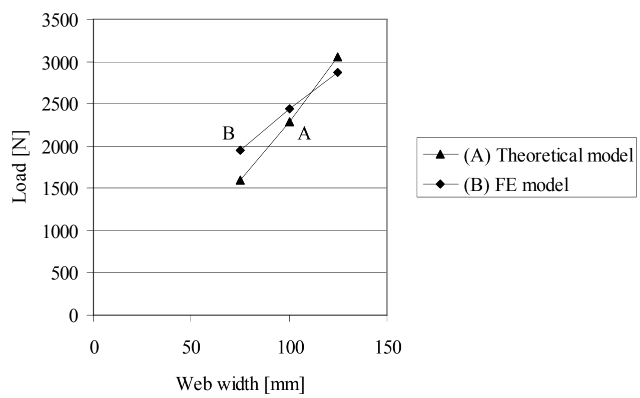

Figure 4, FE model and theoretical model predictions for varying web width

The theoretical model and the finite element simulation have a very similar behaviour. If the web width is larger, the sheeting height increases and this means a higher bending moment can be resisted. Although a web that is higher is expected to buckle earlier and thus is reducing the ultimate load, this effect cannot be observed here.

Compressed flange width
As for the web width, figure 5 shows the ultimate load for varying flange width as predicted by the theoretical model and the finite element model. The figure shows that the model and simulations do not have the same behaviour, although quantitatively the values are in the same range.

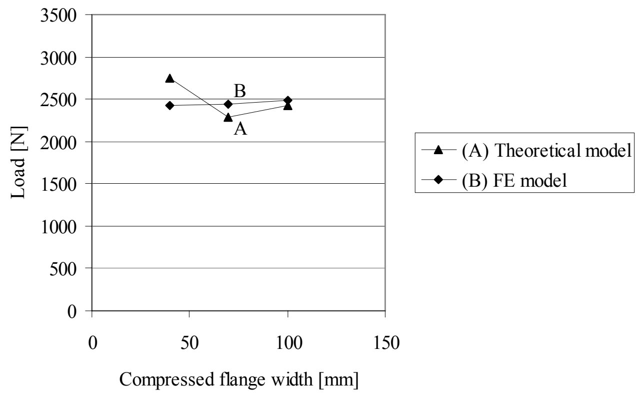

Figure 5, FE model and theoretical model predictions for varying flange width

Angle between web and flange

For varying angle between web and flange, an angle of 50 degrees -simulation "F"- shows convergence problems. The convergence problem context and their possible causes are presented in [Klei06a]. For the remaining two simulations, a good correlation is found with the theoretical model.

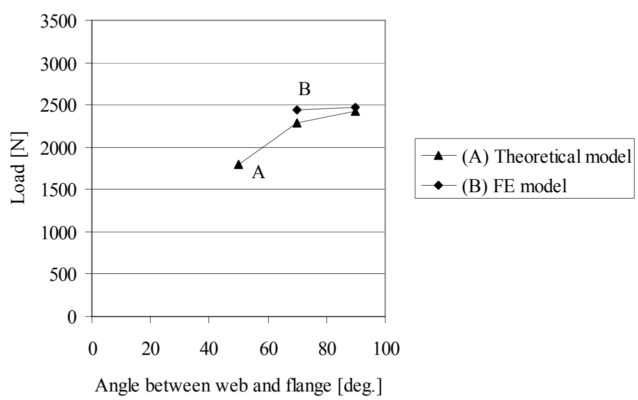

Figure 6, FE model and theoretical model predictions for varying angle between web and flange

Corner radius

Normally, for short span sheeting, the corner radius has a large influence on the failure mechanism to occur. However, for normal to large span sheeting, figure

7 shows that the ultimate load differs only slightly if the corner radius is varied. The figure shows also an almost perfect correlation between the FE model and the theoretical model. The smallest corner radius (1 mm) in combination with the section variable values as shown in table 2 results in convergence problems of the simulation, see [Klei06a] for more details.

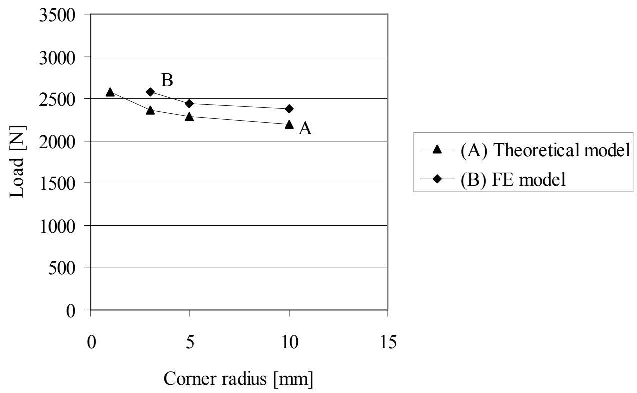

Figure 7, FE model and theoretical model predictions for varying corner radius

Yield strength

The ultimate load is more or less linearly related to the yield strength. This is true for both the FE model and the theoretical model as is shown in figure 8. Also here, an almost perfect correlation exists between the two models.

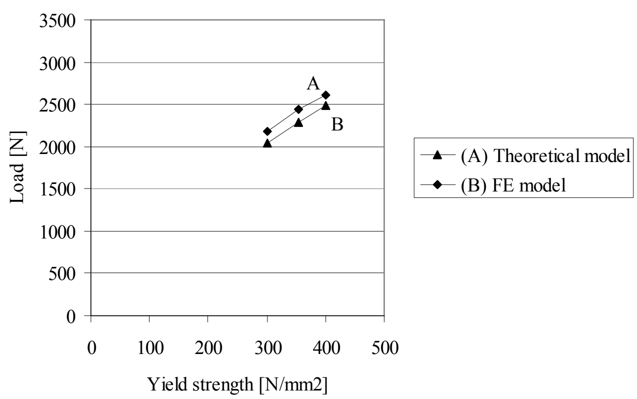

Figure 8, FE model and theoretical model predictions for varying yield strength

Plate thickness

FE model and theoretical model results for a varying plate thickness are shown in figure 9. There is an overestimation of the theoretical model for larger thicknesses, but this overestimation is small compared to the absolute increase in strength. The models have a comparable behaviour for a changing plate thickness.

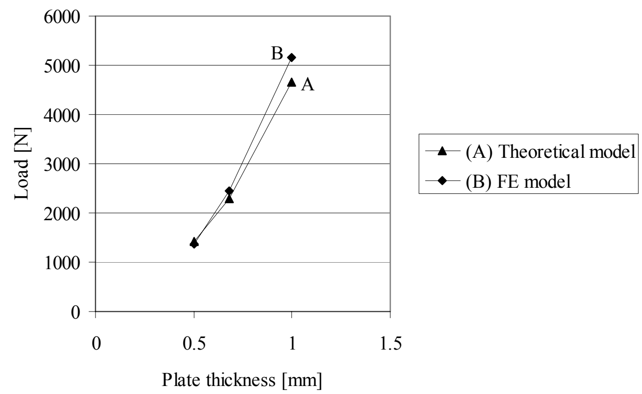

Figure 9, FE model and Theoretical model predictions for varying plate thickness

Span length

For varying span length, the theoretical model and the FE model yield almost the same results, as shown in figure 10. The span length has quite some influence on the ultimate load.

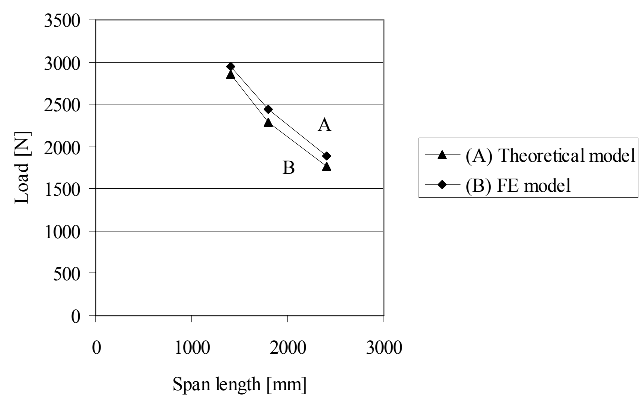

Figure 10, FE model and theoretical model predictions for varying span length

Load bearing plate width
For increasing load bearing plate width, the ultimate load increases both for the theoretical model and the FE model. However, the FE model seems to predict a steeper increase than the theoretical model. An explanation can be the following. If a load application by a load bearing plate is modelled, often four point loads are used. The load bearing plate width thus influences the distance between the point loads. If the bearing plate width is varied, the ratio between the load distances and the compressed flange width and thus the (post-) buckling behaviour of the compressed flange is changed. Possibly, this is not taken into account fully correctly in the theoretical model.

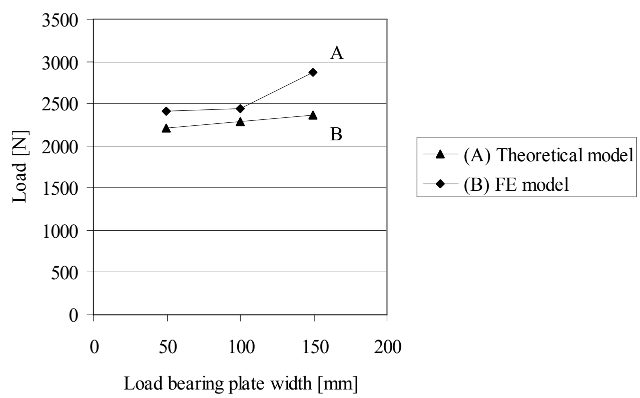

Figure 11, FE model and theoretical model predictions for varying load bearing plate width

Flange out-of-plane deformation at ultimate load
All finite element simulations were used to monitor the compressed flange out-of-plane deformation at ultimate load (note that the initial out-of-plane deformation was zero). The average value of this deformation was 3.35t (with a standard deviation equal to 1.0t). These values are needed to determine the relevant range of plate deformations to study elastic [Bakk06a, Bakk06b] and elasto-plastic plate behaviour.

Conclusions

Theoretical models for first-generation sheeting under combined bending and concentrated load are rare. The latest available model [Hofm01a] performs well compared to experiments.

An existing finite element model was used to study the performance of the theoretical model systematically. For a limited set of cases, the finite element model has convergence problems as explained in another paper [Klei06a].

For varying web width, angle between web and flange, corner radius, yield strength, plate thickness, and span length, the theoretical model performs very well, qualitatively and quantitatively, compared to the finite element model.

For the compressed flange width and load bearing plate width, the theoretical model results show some divergence from the FE model results, although absolute differences remain acceptable, which was also proofed by the set of experiments.

The model has the potential to be used for design rules, if the nonlinear behaviour of the compressed flange can be modelled by a simple yet accurate set of equations for initial imperfections (stress-less imperfections) [Bakk06a] and imperfections caused by a lateral load (stressed imperfections) [Bakk06b].

To make the model possible suitable for second-generation sheeting, research is carried out to find simple equations for stiffened compressed flanges.

Acknowledgements

The M.Sc.-students R.P.A. Verhaegh and W.H. de Groot carried out the finite element simulations presented in this paper. Their help is highly appreciated.

Appendix.-References

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Appendix.-Notation

b	Abbreviated variable. Stands for b_{bffl} [mm].
b_{bf}	Compressed flange width, measured between the points of intersection of the web and flange midlines [mm].
b_{bffl}	Flat compressed flange width [mm]. Also possible is $b_{bf;fl}$.
b_m	Sheet section width [mm].
b_{tf}	Width of flange under tension, measured between the points of intersection of the web and flange midlines [mm].
b_{tffl}	Width of flat part flange under tension [mm]. Also possible is $b_{tf;fl}$.
b_w	Web width, measured between the points of intersection of the web and flange midlines [mm].
b_{wfl}	Flat web width [mm]. Also possible is $b_{w;fl}$.
d_Q, d_P	Distances of point Q and P to line of intersection flange and web [mm].
F_{tf}	Compressive force in compressed flange [N].
f_y	Steel yield strength [N/mm2].
h_m	Sheeting height between flange midlines [mm].
h_w	Sheeting height between flange outer surfaces [mm].
L_{lb}	Load bearing plate width [mm].
L_{span}	Span length [mm]. Also possible is L_{sp}.
P, Q, R	Points at the compressed flange.
r_{bf}	Radius of compressed flange corner midline [mm].
r_{ibf}	Interior radius of compressed flange corner [mm].
r_{itf}	Interior radius of flange under tension corner [mm].
r_{tf}	Radius of flange under tension corner midline [mm].
t	Steel plate thickness [mm].
w_P, w_R	Out-of-plane displacements of point P and R [mm].
θ_w	Angle between web and flange [deg.].
σ_z	Compressive normal stress in compressed flange [N/mm2].