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Abstract

Second-generation sheeting is widely used for cladding and roof construction. At interior supports, it is subjected to combined bending moment and concentrated load. Unfortunately, design rules for this loading are complicated and do not provide insight in the sheeting's failure behaviour. This means there is a need for a new, insight providing design rule. For first-generation sheeting, a similar problem did exist. The Technische Universiteit Eindhoven (TUE) carried out three research projects [Bakk92a,Vaes95a,Hofm00a] that provided insight in the first-generation sheeting behaviour and resulted in a new, insight providing design rule. The TUE now uses the strategy of these three research projects for a new project on second-generation sheeting [Kasp01a], with the final aim of a new design rule for second-generation sheeting. In this new project, experiments on commonly used (in the Netherlands) second-generation sheeting were carried out. Second-generation sheeting behaviour was compared with first-generation sheeting behaviour. For sheeting with only stiffeners in flange, load falls occur before ultimate load. Stiffeners in the web only result in load falls after the ultimate load. For an experiment with only stiffeners in the web, a finite element simulation was made. The simulation predicts the sheeting behaviour fairly well and indicates how a stiffener affects the sheeting behaviour.

1 INTRODUCTION

Sheeting of thin-walled steel plate is widely used in building construction, where it often is subjected to concentrated load and bending moment. Three generations of sheeting exist, as shown in figure 1. Design rules exist that predict the ultimate combination of concentrated load and bending moment the sheeting can bear [Aisi96a, Cana95a, Euro96a]. Recent research [Hofm00a] showed that these design rules differ in their predictions seriously. One of the possible causes for this is that the design rules are not fully based on physical models but partly on curve fitting of test results. This means also that the design rules do not provide much insight in sheeting behaviour.

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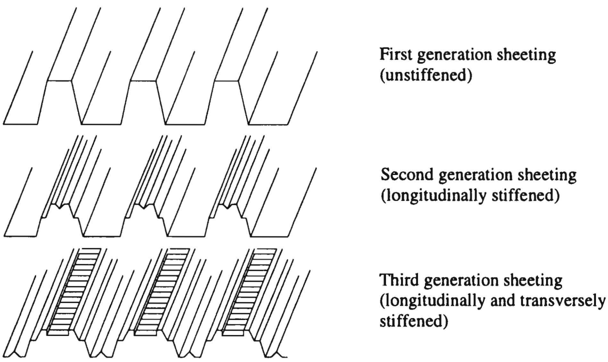


Figure 1, three generations of sheeting.

Since 1986, the Technische Universiteit Eindhoven carries out research to develop new and better design rules for sheeting. These new rules should be based on mechanical models, should be accurate, and should provide insight. This paragraph will give a brief overview of the research carried out until now. From 1985 to 1992, M.C.M. Bakker carried out research on first-generation sheeting using small span (0-39.4 in., 0-1000 mm) experiments, loading hat-sections with concentrated load or with concentrated load and bending moment [Bakk92a]. The load-deformation behaviour and the (post-) failure modes were carefully studied. It was found that two post-failure modes can occur: the rolling and the yield arc modes, see figure 2.

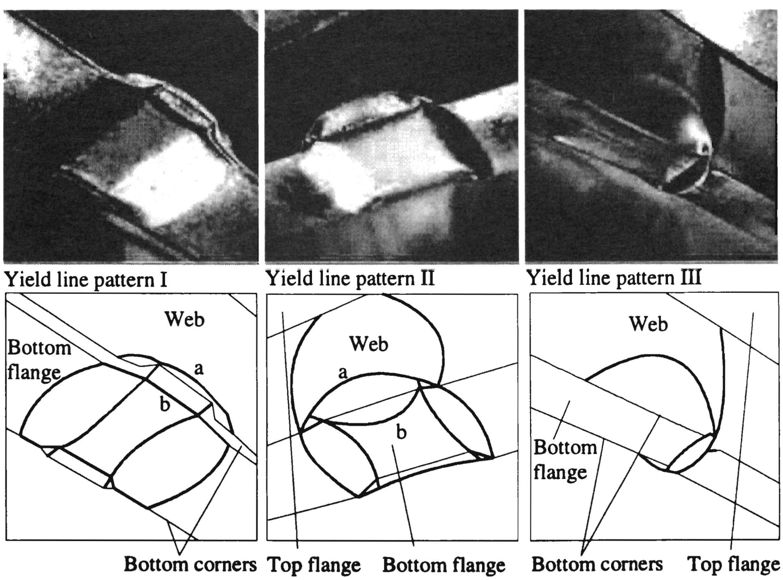


Figure 2, post-failure modes.

For the rolling post-failure mode, a theoretical yield line model was developed, that predicts the load at which the post-failure mode initiates. The yield line model needs information about the elastic cross-section deformation of the sheeting. During the research of Bakker, this information was provided by means of experimental data. In 1995, M.J. Vaessen developed a mechanical model for the elastic cross-section deformation [Vaes95a, Bakk99a]. From that moment on, the model of Bakker could be used without using any test results. In 1995, H. Hofmeyer started research on first-generation sheeting using normal span (23.6-94.5 in., 600-2400 mm) experiments, loading hat-sections with concentrated load and bending moment [Hofm00a]. The span length of the three-point bending experiments (23.6-94.5 in., 600-2400 mm) represents a normal span length (78.7-236.2 in., 2-6 meters) in practice. The experiments showed that three post-failure modes occurred after ultimate load: the rolling, the yield-arc, and the yield-eye post-failure modes, see figure 2. Theoretical models (developed for each post-failure mode) showed why a specific post-failure mode occurred [Hofm00b]. Finite element models showed that at ultimate load two ultimate failure modes exist: the rolling and the localised yield failure mode. The last one seemed to be the most relevant failure mode in practice and for this mode a mechanical model was developed. The mechanical model performs as well as the current design rules and is purely theoretical [Hofm00c].

Having developed a mechanical model predicting fully theoretically the ultimate load of first generation sheeting, the following three questions arose:

1. Can we use the knowledge acquired with first generation sheeting for the second generation? How much differs the behaviour of second-generation sheeting from that of first generation sheeting?

2. Can we simulate the behaviour of second generation sheeting with finite element models (the previous research indicated that fem-simulations increased insight)?

3. If the behaviour of first- and second generation sheeting is more or less the same, is it possible to use the models already developed for the first-generation to predict the ultimate load of the second generation sheeting?

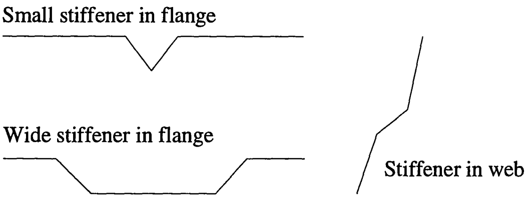
This paper presents research carried out by M. Kaspers in 2001 to answer the questions listed. Experiments, a finite element model, and the existing mechanical models were used. Each of these three items will be presented in a separate section. It should be noted that the authors are fully aware of the fact that many excellent articles exist on the subject of second-generation sheeting, however they are not presented here. This because this paper and the work of M. Kaspers only try to investigate whether the research-methodology developed in Eindhoven for first-generation sheeting can be applied to second-generation sheeting.

2 EXPERIMENTS

As mentioned in the previous section, experiments on second-generation sheeting have been carried out. The most important aim of the experiments was to study the difference in behaviour between first- and second-generation sheeting behaviour.

2.1 Test specimens

A selection of commercially available second-generation sheeting was made. Second generation sheeting differs from first-generation sheeting by longitudinal stiffeners in webs and/or flanges. In this research, stiffeners in the top flange are not observed because their influence on the sheeting behaviour is can be neglected. Most often, these longitudinal stiffeners can be categorised as shown in figure 3 on the top. On the bottom, a table classifies every type of second-generation sheeting.



		Stiffeners in web		
		0	1	2
Stiffeners in bottom flange	0	**W0-F0**	**W1-F0**	**W2-F0**
	1 small	**W0-F1s**	W1-F1s	W2-F1s
	1 wide	**W0-F1w**	W1-F1w	W2-F1w
	2 small	W0-F2s	W1-F2s	W2-F2s
	2 wide	W0-F2w	W1-F2w	W2-F2w
	W-Stiffeners in web F-Stiffeners in flange w-wide stiffener s-small stiffener			

Figure 3, classification of stiffeners and sheeting types having specific stiffener layout.

A selection has been made by only taking the sheeting types that are marked bold in the table, for the following three reasons. By only using a stiffener in the web or in the flange, the differences between first- en second generation will be more pronounced (1). Every stiffener type is present (2). Finally, sheeting type W2-F0 was included because this type is very often used in practice (3). Table 1 shows the data for all experiments carried out. Figure 4 gives an overview of the specimens.

The span length of the three-point bending tests (L_{span}) is chosen to be equivalent to the largest span (of a two-span configuration in practice) allowed according to the manufacturer. The load bearing plate width L_{lb} is given by manufacturer. To prevent load-distribution along sheeting width during failure, only one section (2 webs, 2 half top-flanges, 1 bottom flange) of the sheeting cross-section is used.

2.2 Test rig

The test rig is shown in figure 6. A load bearing plate loads the hat-section deformation controlled. At the left and right side the hat-section is supported in vertical direction, in horizontal direction free movement is possible. Strips bolted to the bottom flange prevent spreading of the webs, and two strips are used to avoid sway of the webs. A measurement strip and two displacement indicators measure the indentation of the cross-section (web crippling deformation). Furthermore, the beam deflection is measured and the support-rotation (see figure 6).

Table 1, test specimens, measured values, averaged over 2 specimen for each type, see figure 5 for explanation of variables.

Type	$1/2b_{tf}$ [in.]	r_{tf} [in.]	b_w [in.]	θ_w [deg.]	r_{tf} [in.]	b_{bf} [in.]	L_{span} [in.]	L_{lb} [in.]	t [in.]	f_y [psi]
W0-F0	2.528	0.185	1.646	75.2	0.134	1.524	43.307	1.969	0.040	54348
W1-F0	2.661	0.169	4.437	71.2	0.189	1.598	86.614	4.724	0.031	47101
W2-F0	2.362	0.189	6.488	68.8	0.134	1.602	110.236	6.299	0.030	45652
W0-F1w	0.850	0.272	3.020	49.7	0.331	6.528	55.118	1.575	0.030	54783
W0-F1s	0.488	0.142	2.469	76.4	0.118	5.831	59.055	3.150	0.029	58696

W1-F0	Stiffener web	θ_{w1} [deg.]	θ_{w2} [deg.]	s [in.]	r_{x4} [in.]	b_{xc} [in.]	r_{x3} [in.]	$\theta_{x3}=\theta_{x4}$ [deg.]
		74.3	74.3	1.181	0.445	18.6	0.732	54.8
W2-F0	Stiffener web top	θ_{w1}	θ_{w2}	s	r_{x4}	b_{xc}	r_{x3}	$\theta_{x3}=\theta_{x4}$
		76.4	73.5	1.197	0.327	0.697	0.366	48.2
	Stiffener web bott.	73.5	72.8	1.205	0.362	0.705	0.417	46.5
W0-F1w $b_{xa}=b_{xc}=0$	Stiffener flange	r_{x1} [in.]	θ_{x1} [deg.]	r_{x2} [in.]	b_{xb} [in.]	r_{x3} [in.]	θ_{x4} [deg.]	r_{x4} [in.]
		0.622	14.1	0.547	1.315	0.445	12.7	0.445
W0-F1s $b_{xa}=0$	Stiffener flange	r_{x1} [in.]	$\theta_{x1}=\theta_{x2}$ [deg.]	b_{xa} [in.]	$r_{x2}=r_{x3}$ [in.]	b_{xc} [in.]	$\theta_{x3}=\theta_{x4}$ [deg.]	r_{x4} [in.]
		>0.551	18	1.122	0.205	1.193	17	0.512

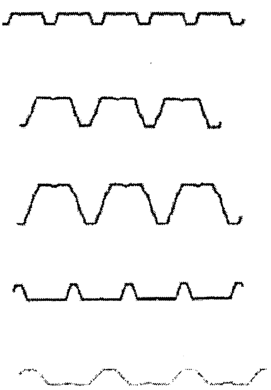


Figure 4, schematic overview of tested specimens, from top to bottom W0-F0, W1-F0, W2-F0, W0-F1s, W0-F1w.

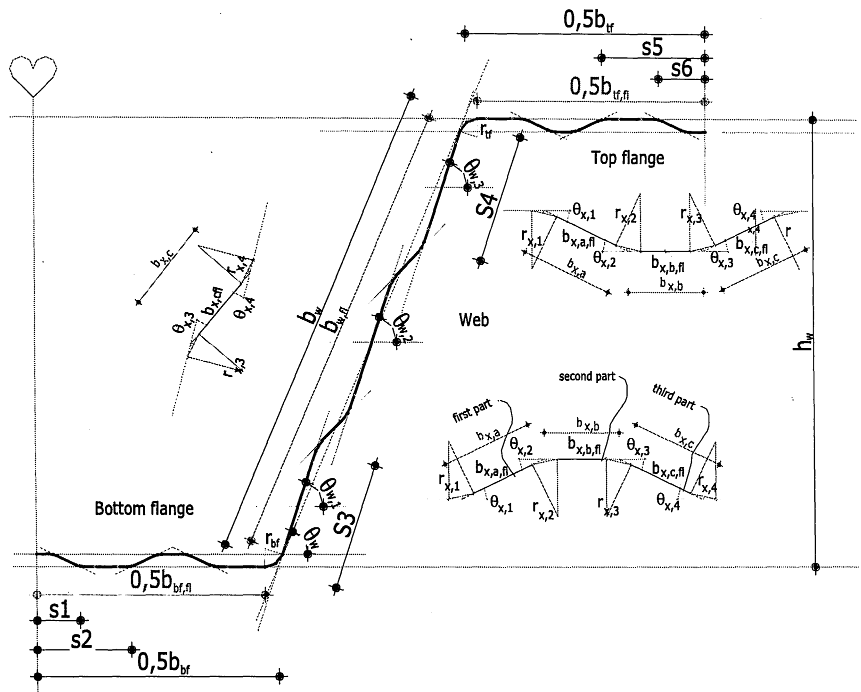


Figure 5, exact geometry of second generation sheeting.

2.3 TEST RESULTS

For every type of sheeting test results are presented. Test results presented are a load versus web-crippling diagram, a description of the post-failure mode, and if applicable some remarks. As already mentioned, every sheeting type was tested twice. If no large differences exist between the two tests, only one of each type is presented here.

For the description of the experiments, it is of importance to define the definitions of elastic behaviour, buckling, and mode jumping as used in this paper. If a sheet-section is loaded, it will first deform elastically. This elastic deformation can look like a (locally) buckled section, due to the eccentric load application, see figure 7 on the top. However, the section (and more specific the compressed bottom flange) is not really buckling, but deforming non-linearly. If a non-eccentric load distribution would exist (i.e. a section is loaded by pure bending moment), the section could buckle in a shape similar to the geometry as shown in figure 7 on the top. For the experiment as presented here buckling does not occur, but elastic deformation does. Mode jumping is a phenomenon that one buckled (or deformed) shape deforms instantly into another shape during a load increment, see figure 7 on the bottom. This happened for some experiments after elastic deformation: some parts were locally compressed further en changed their geometry. This will be presented in more detail in the presentation of the experiments.

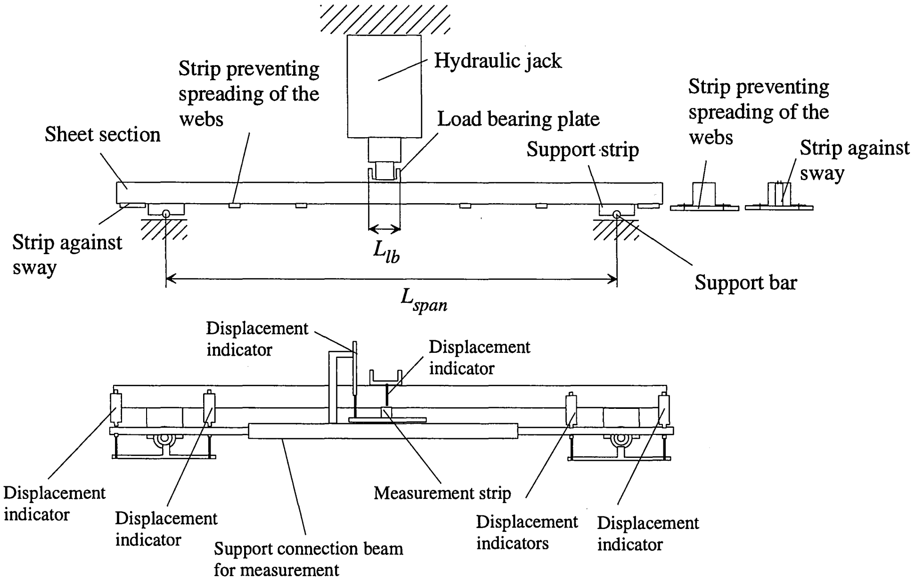


Figure 6, test rig.

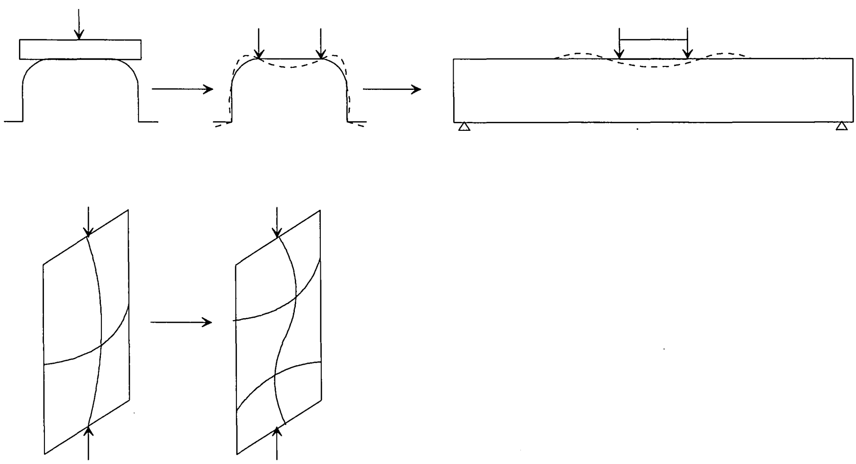


Figure 7, elastic deformation (on the top) and mode-jumping (on the bottom).

W0-F0 (test I and II)
For these two tests, a normal yield-arc post-failure mode occurred, as shown by the yield-line patterns and the load versus web crippling deformation curves, see figure 2 for a representative (schematic) example.

W1-F0 (test I and II)
Before the ultimate load, the webs beneath the load bearing plate deform a bit outwards elastically. The stiffeners (left and right) at this location are also compressed. At or after ultimate load a yield line in the web is growing and it moves from the (compressed) bottom flange to the top flange (under tension) and passes the stiffener in the web. In the load versus web crippling deformation curve two irregularities can be seen. It is thought that the first load fall indicates the yield line passing the upper corner of the stiffener and the second fall indicates the yield line passing the bottom corner of the stiffener. The observations of the second test are equal to the first test. The hypothesis that the load falls indicate that the yield line passes the upper and the lower corner of the stiffener as described is confirmed. A yield-arc post-failure occurs, however, the yield line in the web has no arc-like geometry, but a more v-shaped geometry, see figure 8.

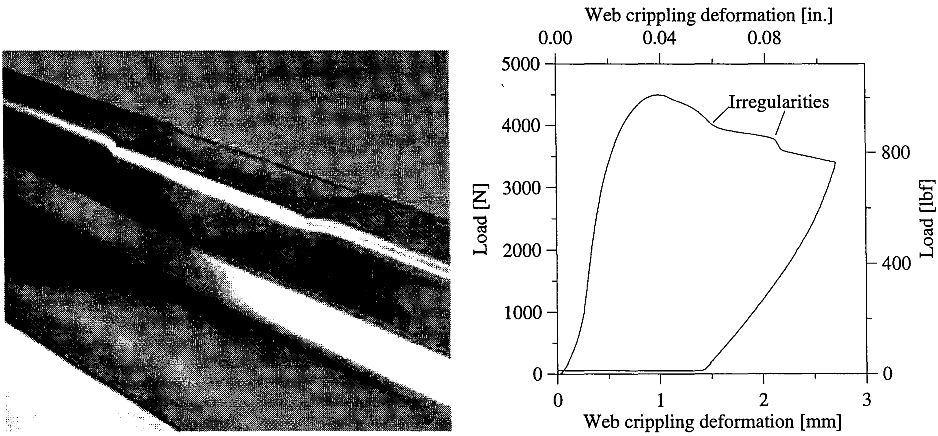


Figure 8, yield line pattern and load versus web crippling deformation for W1-F0 (compressed bottom flange is positioned on the top here).

W2-F0

While the load is increasing, buckles are recognised in the web, beneath the load bearing plate, in the plate in between the two web stiffeners. Beneath the load bearing plate, the webs are slightly pressed out but not as much as for W1-F0. The pressed out form passes the upper stiffener (stiffener near to the load bearing plate) and for increased loading passing the stiffener near the bottom. Immediately after the ultimate load (point 4 in figure 9), the web is pushed inwards (location A in figure 10) with a popping sound. This can be seen in figure 10. Hereafter (point 5), another part of the web is pushed in (location B), also with a popping sound. At point 6, the yield-arc post-failure mode is changing into a yield-eye post-failure mode (see for details

[Hofm00a]). At point 7, the upper stiffener is pushed firmly outwards beneath the load bearing plate. After further deformation, at point 8, the web is pushed in for the third point, at location C.

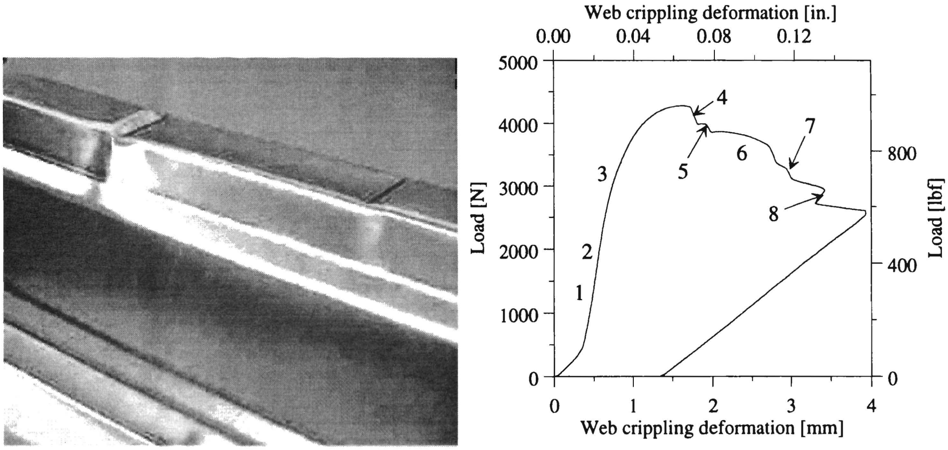


Figure 9, yield line pattern and load versus web crippling deformation for W2-F0.

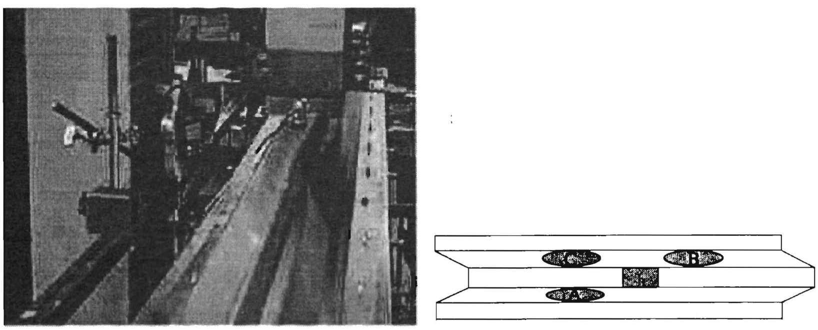


Figure 10, web pushed inwards and locations.

<u>W0-F1w (I)</u>

After elastic deformation (the webs are pressed out), just before the ultimate load is reached, mode jumping occurs in the bottom flange with popping sound. This mode jumping can be seen in figure 11 as a small irregularity in the curve. After ultimate load an other irregularity in the curve can be seen, but this can not be combined with visual clues. Finally, a yield-arc post failure mode occurs.

WO-F1w (II)

This test behaves the same as the first test. After ultimate load, the yield-arc post-failure changes into a yield-eye post-failure mode. After ultimate load, no irregularity in the load versus web crippling curve occurs.

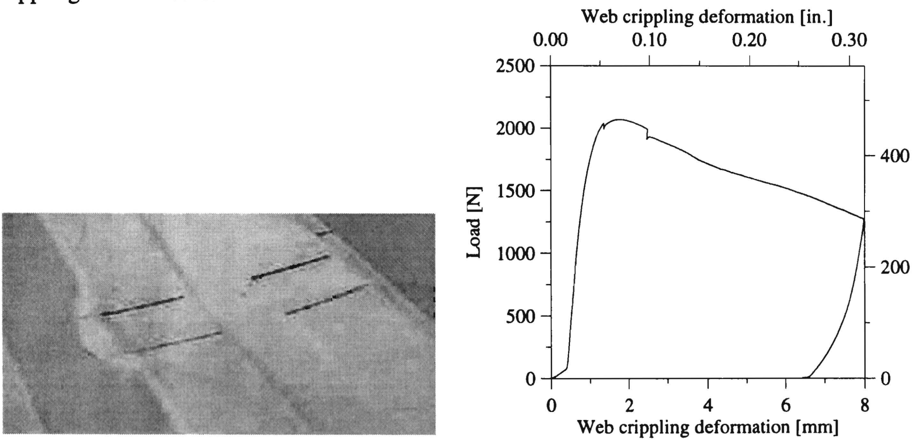


Figure 11, yield line pattern and load versus web crippling deformation for WO-F1w.

WO-F1s (I and II)

Elastic deformation occurs before ultimate load. After ultimate load a yield-eye post-failure mode occurs. Before the ultimate load the curve in figure 12 shows an irregularity, but this phenomenon can not be combined with visual clues. Possibly, mode jumping occurs in the top flange.

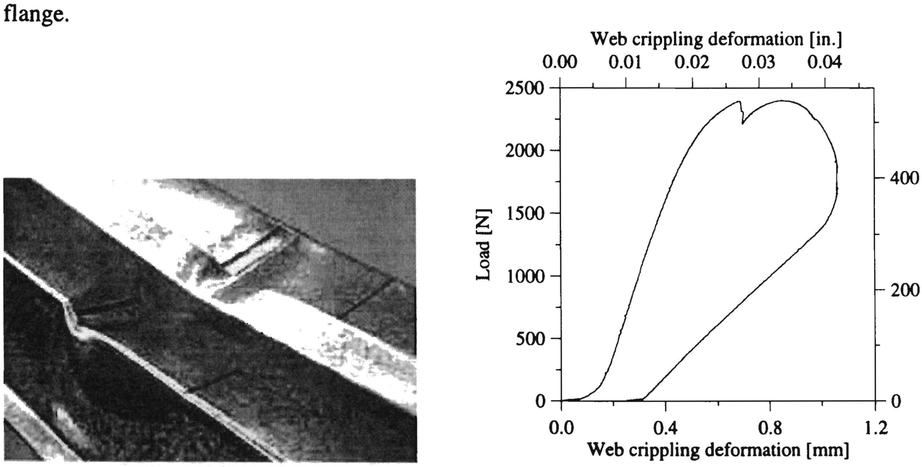


Figure 12, yield line pattern and load versus web crippling deformation for WO-F1s.

2.4 Conclusions

The five types of steel sheeting are chosen as explained, based on the type and number of stiffeners in web and flange. It is possible that other types of sheet sections do not show the same behaviour as found for the steel sheeting tested in this project.

The behaviour of second-generation steel sheeting is different from the behaviour of first-generation steel sheeting. Especially important are the irregularities found in the load web crippling diagram. These are probably related to mode jumping in web or flange. A distinction can be made between sheet sections with stiffeners in the web and stiffeners in the flanges. Specimens with stiffeners in the web show irregularities after failure and specimens with stiffeners in the flange show irregularities before failure.

The same post-failure modes occur for second-generation as those known for first-generation steel sheeting, except that the rolling post-failure mode was not observed.

3 FINITE ELEMENT SIMULATIONS

Previous research [Hofm00a] showed that finite element simulations can seriously improve knowledge about sheeting behaviour. In this section it will be investigated whether second generation sheeting (more precisely the experiments presented in the previous section) can be simulated by a finite element model as well.

As was shown in the previous section, irregularities in the load-web crippling curves can occur. These irregularities are possibly indicating mode jumping in flange or webs, which is a highly dynamic phenomenon, and has states in time for which static equilibrium does not exist. The finite element program used in this research, Ansys 5.6 [Ansy99a], does not have an explicit solving method, which is generally believed to be needed to tackle mode-jumping. This means that the finite element program used cannot tackle the irregularities mentioned.

As discussed in section 2.3, stiffeners in the flange lead to irregularities before the ultimate load, sections with stiffeners in the web lead to irregularities after the ultimate load. This means sections with stiffeners in the web can be modelled with Ansys 5.6 until and at ultimate load. This will be presented in this section. Due to limited time for the research only one experiment has been simulated so far. Sections with stiffeners in the flange will be more difficult to simulate. At this moment, simulations with ANSYS/LS-DYNA (an explicit, dynamic simulation environment) are proposed for these sections.

3.1 Simulation of experiment W1-F0 (I)

Geometry and mesh

The experiment fails by a symmetric post-failure mode (yield-arc) and thus a quarter model is used. A coarse mesh is used for small stress gradients, a fine mesh for large stress gradients, see figure 13. The stiffener's corner radii are modelled with 3 elements along the cross-section. A substructure has been used to model the linearly behaving parts. No imperfections are modelled, there is a uniform cross-section in length direction.

Elements

Elements used are shell elements "SHELL43" with four nodes (with 6 degrees of freedom each) and extra displacement shapes. The elements are capable of describing plasticity, large deflections and large strains [Ansy99a]. The element uses a 2x2-integration scheme for in-plane integration and 5 integration points through the thickness.

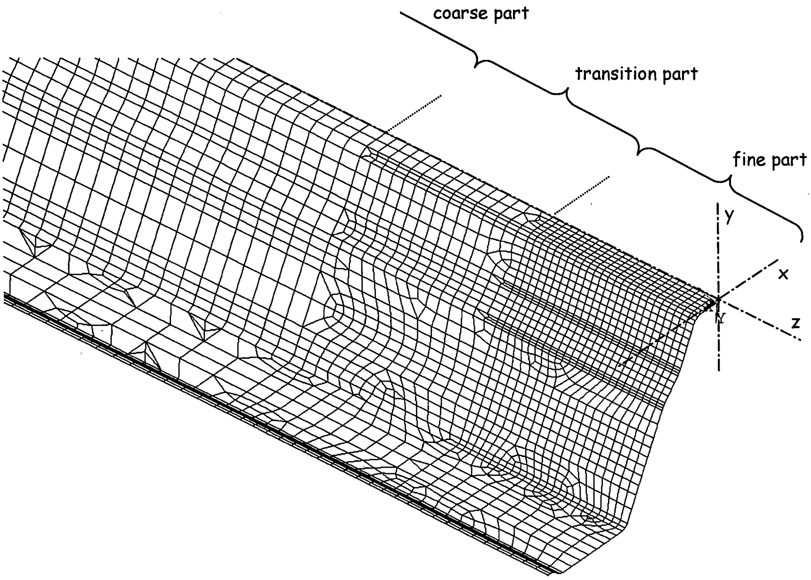


Figure 13, mesh for finite element model.

Material model

Experiments in the laboratory provide the engineering stress and strain, which have to be converted to real strain and stresses. These real stress and strain have been used as input for the program. The core thickness is used for the steel plate thickness, ignoring the thickness of the zinc layers.

Loading and boundary conditions

A load-bearing plate has been modelled. Contact elements are placed between the sheet section and the load-bearing plate, as explained in [Hofm00a]. Contact elements used are

"CONTAC49". Symmetric boundary conditions have been modelled, furthermore the supports, the strips preventing spreading of the webs and the boundary conditions of the load bearing plate have been modelled, for details see [Kasp01a].

Model quality

Some checks have been carried out to check the correctness of the finite element model. The load application is checked for elastic behaviour by running models with only a prescribed node displacement, or multiple prescribed node displacements (1). A model without a substructure is used to check the correctness of the substructure (2). The (in this case irrelevant) influence of increased yield strength near the corner radii is checked (3). Finally, residual stresses were applied and their effects in this case can be neglected (4).

Results

Figure 14 shows the load versus beam deflection and the load versus web crippling deformation for the experiment and the finite element simulation.

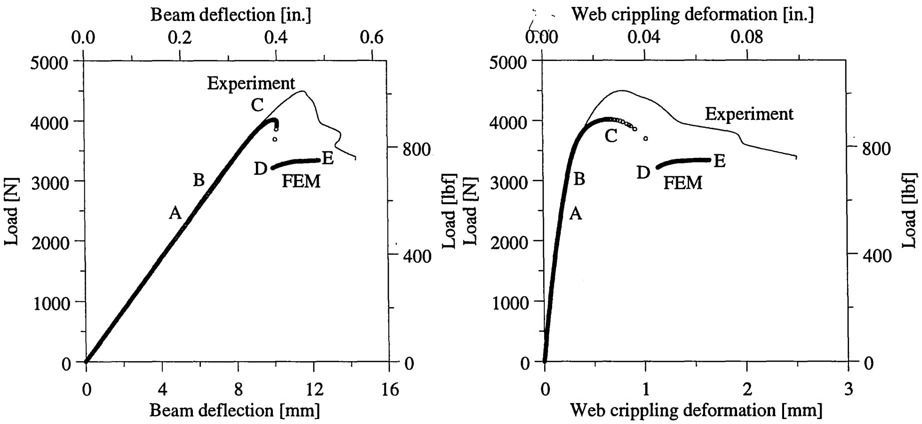


Figure 14, load versus beam deflection and web crippling.

At point A, figure 14, yielding starts on the outside of the sheet section, at the location of contact between load bearing plate and section. At point B, also at the inner surface yielding starts. Near the ultimate load, at point C, yield lines are occurring as shown in figure 15. At point D, the upper corner radius of the stiffener starts to yield. Finally, at point E, a yield line pattern can be seen that is comparable to pattern found in the experiment, see figure 15.

The elastic stiffness of the finite element simulation is equal to the elastic stiffness of the experiment. Yielding starts in the bottom flange under the load bearing plate. The ultimate load predicted by the finite element calculation is 4016 N, that is 89.2 % of the maximum load found with the experiment (4502 N.) This difference can be due to the lack of modelling imperfections.

After ultimate load, the finite element model shows divergence problems (figure 14, the lack of results between point C and D. For larger deformations the solution converged again.

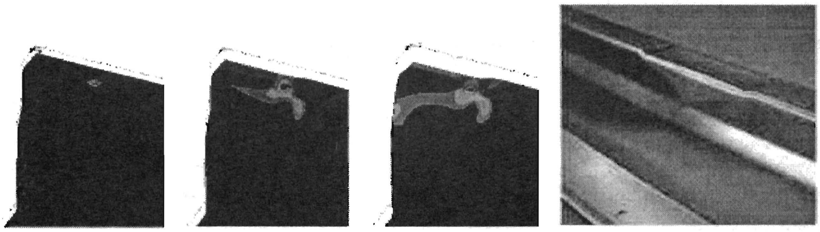


Figure 15, yielding as indicated by the finite element model (from left to right: point A, C, E and the experiment).

3.2 STIFFENER APPLICATION

To investigate whether the stiffener could be the cause for divergence, and to investigate the effect of the stiffener, a finite element model for experiment W1-FO(I) without a stiffener was used. The results are shown in figure 16. This figure also shows that the application of a stiffener improves the ultimate load significantly.

Furthermore, divergence problems vanish for a section without a stiffener. The divergence problems might thus be related to stiffener application. The simulation with stiffener shows that at the point of divergence the stiffener is pushed out (figure 17), something that was also observed in the experiments. This does not occur for the simulation without a stiffener.

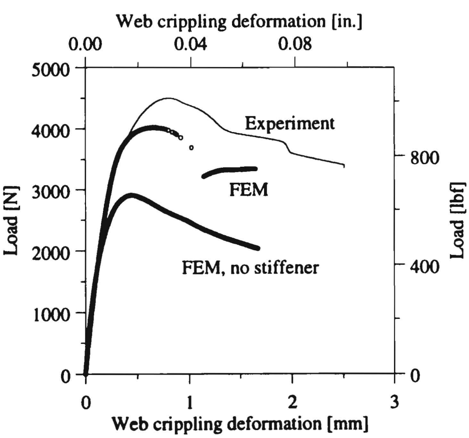


Figure 16, lack of the stiffener has a great effect on the ultimate strength but avoids divergence problems.

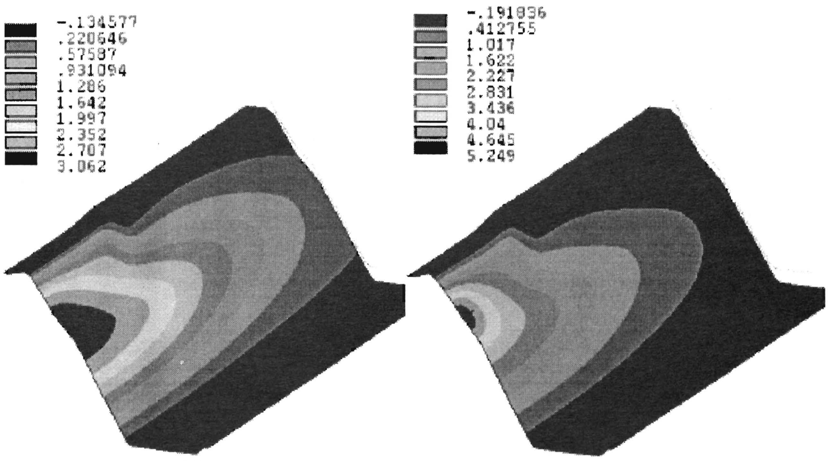


Figure 17, on the left a section before divergence, on the right after divergence. Note that the stiffener is pushed out. See for each section the geometry of the left edge near the highest stresses.

3.3 Conclusions

Although only one experiment was simulated, it is believed that second generation sheeting without stiffeners in the flange (where no mode-jumping occurs before failure) can be modelled using finite element models. This until and at ultimate load. The ultimate load was predicted within 10 % accuracy.

After ultimate load, irregularities in the load deformation curve occur. These are possibly related to mode jumping: experiments and the finite element simulation show the stiffener is pushed out. The finite element model predicts this behaviour qualitatively, but the load deformation curves of experiment and simulation are too much different. Besides this, the finite element simulation shows divergence problems when the stiffener is pushed out.

For sections with stiffeners in the flange and for sections with stiffeners in the web after ultimate load, the finite element model used (static, implicit) is not suitable. In future a dynamic, explicit model will be tried.

A stiffener in the web significantly increases the ultimate load of the section simulated.

4 MODEL FOR FIRST-GENERATION SHEETING

4.1 Introduction

As already mentioned in section 1, a mechanical model was developed to predict the ultimate failure load for first-generation steel sheeting [Hofm00a]. For first-generation steel sheeting this model performs as well as the current design rules and it provides insight into the sheeting behaviour. In this model, first the elastic cross-section deformations resulting from the concentrated load are determined. Then, these deformations are used as estimation for the imperfection of the bottom flange. This bottom flange is under compression due to a bending moment in the sheeting. A solution of Marguerre's equations is then used to determine the load for which the bottom flange (under compression and with an initial imperfection) will start to yield.

In this section, this model will be applied to the tested (second-generation) sheet sections, and results will be discussed.

4.2 RESULTS OF MECHANICAL MODEL

For the mechanical model, real measured sheet properties are used. Stiffeners are ignored. For results see table 2. The mechanical model calculates a web crippling stiffness (k_{model}). This web crippling stiffness is compared with the web crippling stiffness found in the load versus web crippling graphs of the experiments (k_{exp}). Further the ultimate load ($F_{u,\ model}$) is calculated and compared with the experimentally determined ultimate load ($F_{u,exp}$). Finally $F_{u,model}$ is calculated with k_{exp} in stead of k_{model}.

Table 2, results of the first-generation mechanical model.

	k		F_u		F_u
	Model [lbf/in.] k_{model}	Measured [lbf/in.] k_{exp}	Model [lbf] $F_{u,model}$	Measured [lbf] $F_{u,measured}$	$F_{u,model}$ with k_{exp} [lbf]
W0-F0(1)	165197	13413	531	646	272
W0-F0(2)	164923	13870	544	637	284
W1-F0(1)	78124	79225	633	1006	633
W1-F0(2)	81908	51884	649	1000	582
W2-F0(1)	112844	40183	743	958	567
W2-F0(2)	108324	54910	738	956	623
W0-F1s(1)	49088	60732	351	535	355
W0-F1s(2)		71348		544	
W0-F1w(1)	24327	40754	396	463	407
W0-F1w(2)	26753	50058	380	411	391

For sheeting without stiffeners in the web or bottom flange (first-generation sheeting) the mechanical model should give (and gives) good results. Looking at the results it is strange that the web crippling stiffness predicted by the model gives bad results, while the ultimate loads calculated with this bad web crippling stiffness are in good accordance with the test results.

For sheeting with stiffeners in the web, it is striking that the web crippling stiffness agrees quite well, whereas the ultimate load is not predicted accurately by the model. The finite element simulation of W1-F0 showed yielding in the bottom flange long before ultimate load. This is not in accordance with one of the main assumptions in the model and thus can be a possible explanation for the bad results. Furthermore, for a section with and without web stiffener, the finite element simulation (section 3.2) showed no large differences in web crippling stiffness, but quite large differences in bottom flange out-of-plane deformation. Research should therefore be carried out on the relationship between web crippling deformation and out-of-plane deformation for the situation with and without a web stiffener.

5 CONCLUSIONS

The conclusions are limited to the scope of the five tested steel sheeting types. It is possible that other types of sheet sections, not considered in this research, do not show the same behaviour as found for the steel sheeting types tested here.

Second-generation steel sheeting types seem to show the same post-failure modes in experiments as known from first-generation steel sheeting. Sheeting with stiffeners in the web show mode-jumping after failure and those with stiffeners in the flange shows mode-jumping before failure.

Although only one experiment was simulated, it is believed that second generation sheeting without stiffeners in the flange can be modelled using finite element models. This until and at ultimate load. The ultimate load was predicted within 10 % accuracy. For sections with stiffeners in the flange and for sections with stiffeners in the web after ultimate load, the finite element model used (static, implicit) is not suitable. In future a dynamic, explicit model will be tried. A stiffener in the web leads to a significantly increased ultimate load for the section simulated.

For sheeting with stiffeners in the web, research should be carried out on the relationship between web crippling deformation and bottom flange out-of-plane deformation for the situation with and without a web stiffener.

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8 NOTATION

$F_{u,exp/model}$	Ultimate load determined by experiment or model [lbf].
f_y	Steel yield strength [psi].
$k_{exp/model}$	Web crippling stiffness determined by experiment or model [lbf/in.].
L_{lb}	Load bearing plate length [in.], shown in figure 6.
L_{span}	Span length [in.], shown in figure 6.
t	Steel plate thickness without zinc layer [in.].

All other variables in table 1 are explained in figure 5. All distances [in.], all angles [deg.].