Abstract

In the present days, thin-walled structural members are getting used more and more in the industrial domain, that's why the research of these type of elements demands a lot of attention. One special place between these elements, is occupied by the cold-formed trapezoidal steel sheets.

The evolution of this domain concluded in appearance of a numerous manufacturers producing trapezoidal steel sheets, for industrial roofing and structure covering. Due to the high competition, the efficiency and accuracy in determining the load carrying capacity of the sheets has a key role. The methods used to achieve these results have to be conformed with the codes and standards of the country where the sheets are going to be in service.

The following study researches the behaviour of trapezoidal steel sheets submitted to bending. The main concept of the paper, is to compare the results of the experimental test, performed at Escola Tecnica Superior d'Enginyeria Industrial de Barcelona with the North-American and European design methods.

Aspects, that are examined in the paper are the failure mode and the types of buckling modes that appear in the sheeting. There is a complex presentation of the researches that the project is based on, the software analyses performed in different programs: CUFSM, Ansys-Mechanical APDL; tend to reproduce the real scale experimental test.

The FEM analysis appears to be a very good scientific tool to identify the behaviour of trapezoidal steel sheets, given the similarities between the model results and the experimental ones. The design methods use different approaches, but converge to affined results.

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1. Introduction

Cold formed steel sheets, due to its strength and durability is the ideal building material for roofs, facades and partition walls. Their main characteristics are that they are lightweight, easy and economical to fabricate, to deliver and to assembly. An extensive selection of high and low profiles gives the client the opportunity to design in complete accordance with their needs. The trapezoidal steel sheets are mounted on the structure by using fasteners that vary depending on which type of profile is chosen.

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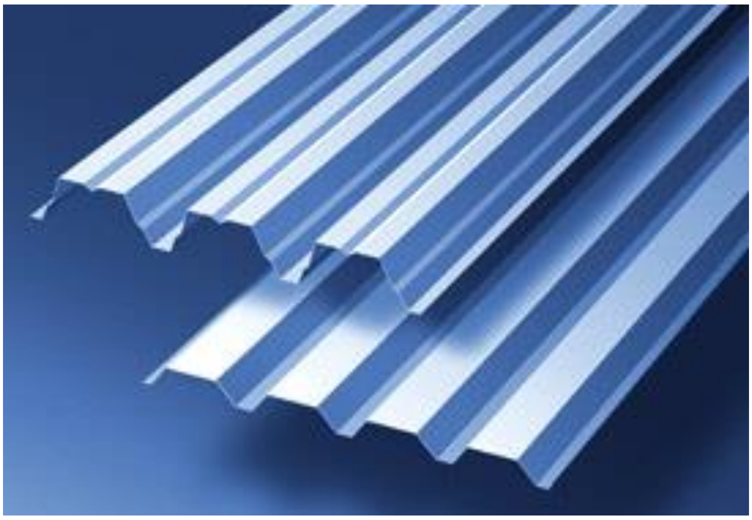


Figure 1: Typical trapezoidal sheets

1.1 Origin of the project

There are a variety of companies that produce trapezoidal steel sheets for different applications. METALPERFIL and EUROPERFIL are local companies from Catalonia, they have a wide range of products for different applications and different type of structures like: industrial premises, hypermarkets, barns and stables, small residential buildings, carports, advertising panels.

This project started as collaboration with METALPERFIL and EUROPERFIL Company in order to improve their list of products, more exactly to find out about the bearing capacity of the steel sheets with different type of sections: H-55, H-68, H-150, EUROCOL 60.

1.2 Motivation

The motivation to participate in this project comes from a personal, commercial and economical aspect. The personal motivation was born from curiosity towards new types of elements used in civil engineering.

The commercial and economical aspects come from the collaboration with METALPERFIL and EUROPERFIL Company, and aim to determine the bearing capacity of the steel sheets. This project also is studying all the parameters that have an influence on the effective properties of the trapezoidal steel sheets.

1.3 Objectives of the project

The main object of the project is to assess different a calculation methods for trapezoidal steel sheets by comparing their results with the results from Ansys Mechanical APDL models and the experimental test results. From these models we can get the data necessary to calculate the ultimate bending moment of the sheets, and the ultimate load that they can withstand. To do this it requires a lot of time and resources so, in order to simplify it, one of the objectives is to generate FEM models using macros created with the Ansys Mechanical commands.

An experiment is conducted and performed in the laboratory of Escola Tecnica Superior d'Enginyeria Industrial de Barcelona on EUROCOL 60, to determine the bearing capacity and the failure mode of the trapezoidal steel sheet. Furthermore, data from previous experiments will also be used.

In the end this study will give us a better understanding about the behaviour of trapezoidal steel sheets with different heights and thickness, with stiffened/ unstiffened webs/flanges; and will allow us to know which is the most efficient design method.

1.4 Scope of the thesis

This particular thesis focuses on assessing the calculation methods in accordance with the North-American, European standards and realize a Finite Element Method model which results together with the calculations converge towards the real scale experimental test results.

2. State of the art

2.1 Cold formed steel

2.1.1 Generalities

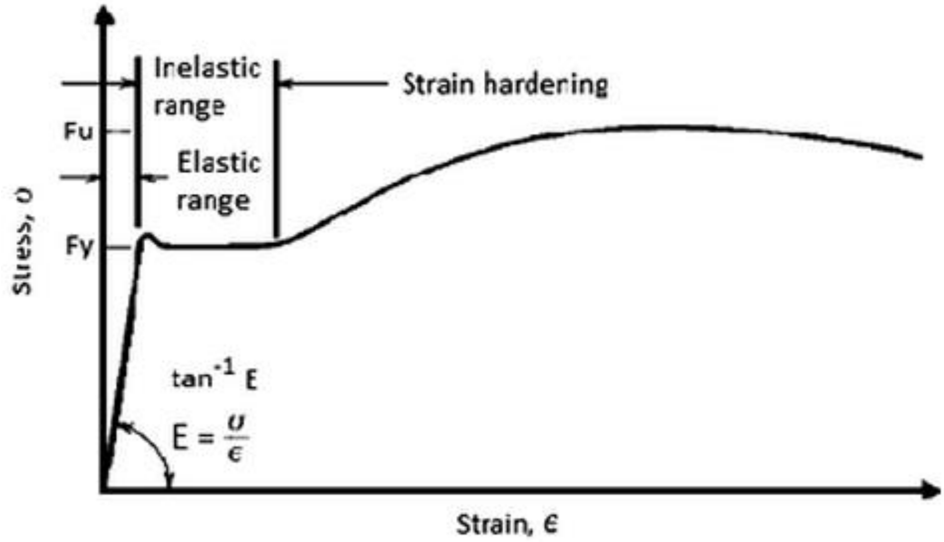
During the XXth century a new type of element started to appear in the industry, used by American and British engineers the cold formed steel profiles. Their list of application kept growing by the time from purlins, to sheeting for roofs and floor decking which is considered the secondary structure for buildings, but nowadays these profiles are used as primary resistance structures as well.

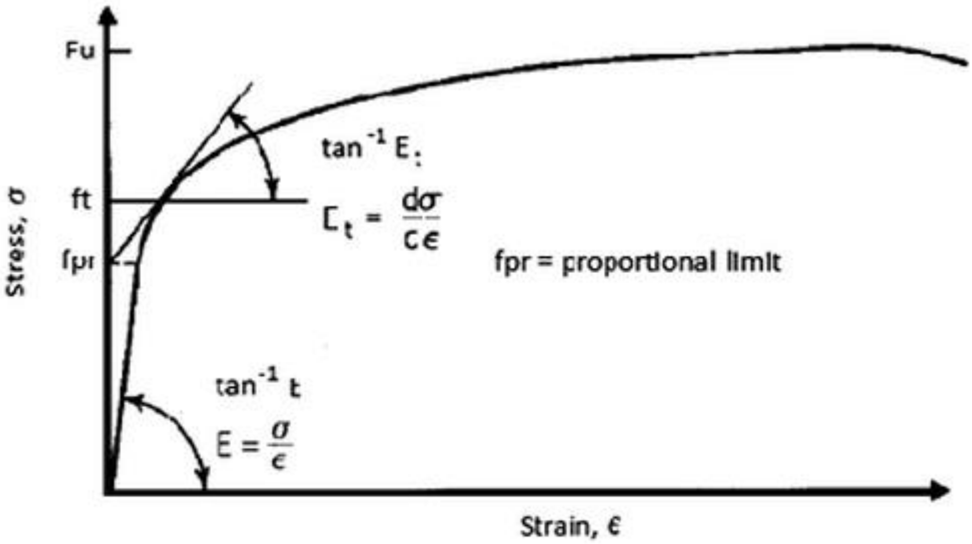
The perspective of cost and efficiency in constructions are being more restrictive than ever, but cold formed profiles excels in resistance/weight ratio, opportunity of rapid transport of the elements, easy and fast assembly and the possibility to recover and recycle the profiles. Being such a new branch in the field of civil engineering, it also created some new and difficult design problems that were rarely encountered in the past. Of course there are similarities in theory, but the use of cold formed steel and small thickness still causes problems for most of the engineers.

The problem usually rises from the fact that the component walls of the section are very slender, so the section will be of class 4 or class 3, according to the Eurocode. When using sections of class 4 we have to take into account the fogging (the loss of stability), thus using the active characteristics of sections which are reduced compared to the real characteristics. In this way local instability, buckling, distortion can mix with global instability and generate a higher sensitivity to imperfections and reducing the bearing capacity of the profiles subjected to compression or bending.

2.1.2 Material

The stress-strain curve describes the material behaviour. The steel grade used to realize these cold formed profiles is very important in determining their bearing capacity. The stress strain graph of steel can be classified in 2 categories: sharp yielding and gradual yielding (Figure 8 and Figure 9).





These two graphs represent the behaviour of cold formed steel sheets during tension tests. In the second graph the steel sheet used for the test has undergone the hard rolling during the manufacturing and it doesn't register a yielding point with a plateau, and as a result the initial slope of the curve has been lowered. This is the behaviour of the annealed steel and the yielding point can be considered the level where the curve becomes horizontal.

As presented before, the advantage of cold forming is that it increases the yield strength of the profiles, being a consequence of cold working well into the strain hardening range. This increase takes place in the zones where the material is deformed by bending or working. Another factor that influences the value of the yielding limit is the number of stiffeners of the walls of the profile.

2.1.3 Corrosion and protection

The non-corrodibility property of the cold formed profiles depends on how aggressive is the surrounding environment and how thick is the applied coating. Cold forming process allows the anticorrosive protection to be applied before lamination without being damaged.

Galvanizing (or zinc coating) of the preformed coil provides very satisfactory protection against corrosion in internal environments. A coating of 275 g/m2 (total for both faces), is the usual standard for internal environments. This corresponds to zinc coating of 0.04 mm. Thicker coatings are essential when moisture is present for longer periods. Other than galvanizing, different methods of pre-rolling and post-rolling corrosion protection measures are also used.

2.1.4 Applications of cold formed profiles

Considering the constant development of this domain, the variety of profiles that can be manufactured, cold formed steel elements has been used approximately in every sector of building constructions.

- Purlins
- Beams, columns
- Solar installations
- Aircrafts, ships
- Industrial buildings- primary and secondary structures

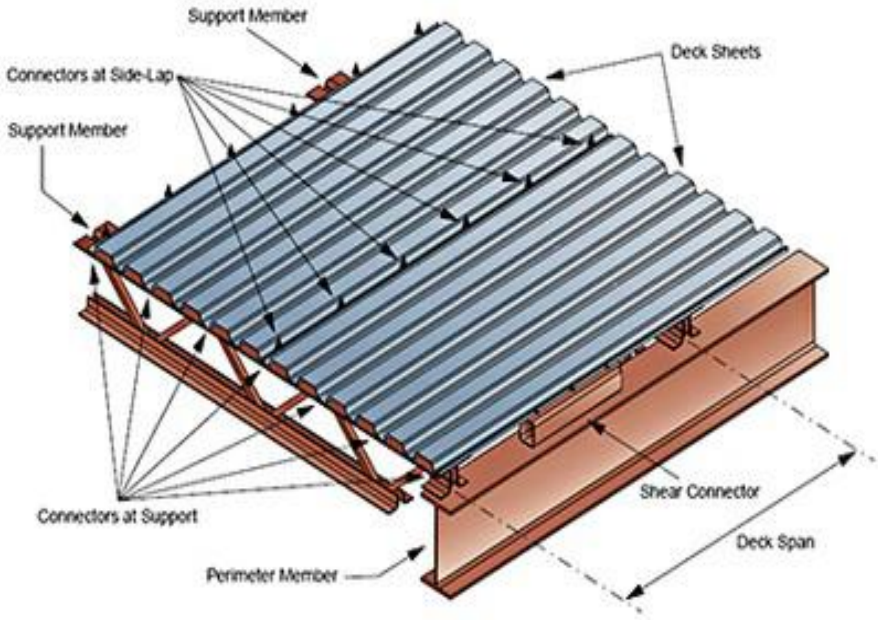


Fig.2 Example for industrial roofing

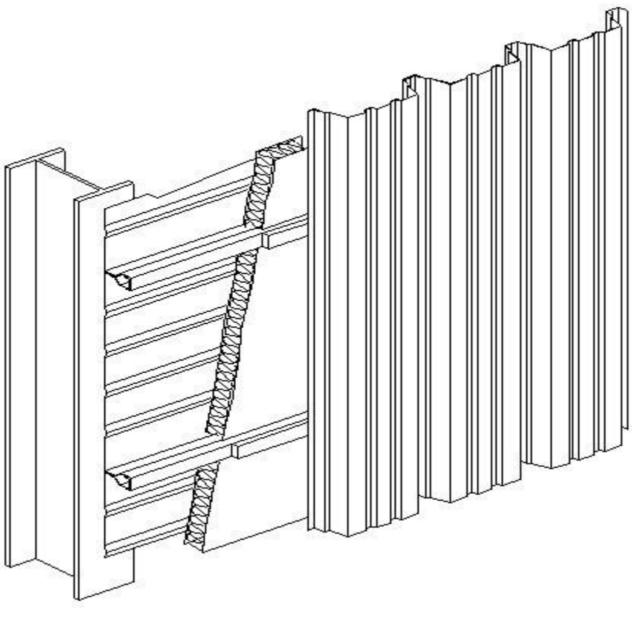


Figure 3 Vertical wall construction

2.1.5 Advantages & Disadvantages

In the following there are some advantageous characteristics of cold formed steel elements compared to the hot rolled profiles. In civil engineering they create a lot of benefits like:

- The variety of manufacturing for different applications
- Higher yield stress as an effect of the cold working
- More economical, especially in the use of lower loads and lower spans
- Fast and precise manufacturing
- Possibility of realizing longer lengths of the profiles
- Easy to transport- compact stacks
- Sheeting and panels can act as a diaphragm
- Great resistance/weight ratio
- Accuracy
- The structure can be recovered

Most of the time cold formed steel profiles serve as secondary structural elements in the civil engineering sector as roofing or cladding In the industrial domain they are very popular considering the advantages listed above. Because of the tendency for lighter structures these elements are used more and more often by designers. As disadvantages we can specify the reduced ductility, sensibility against fire, when buckling modes combine they become very unstable and unpredictable.

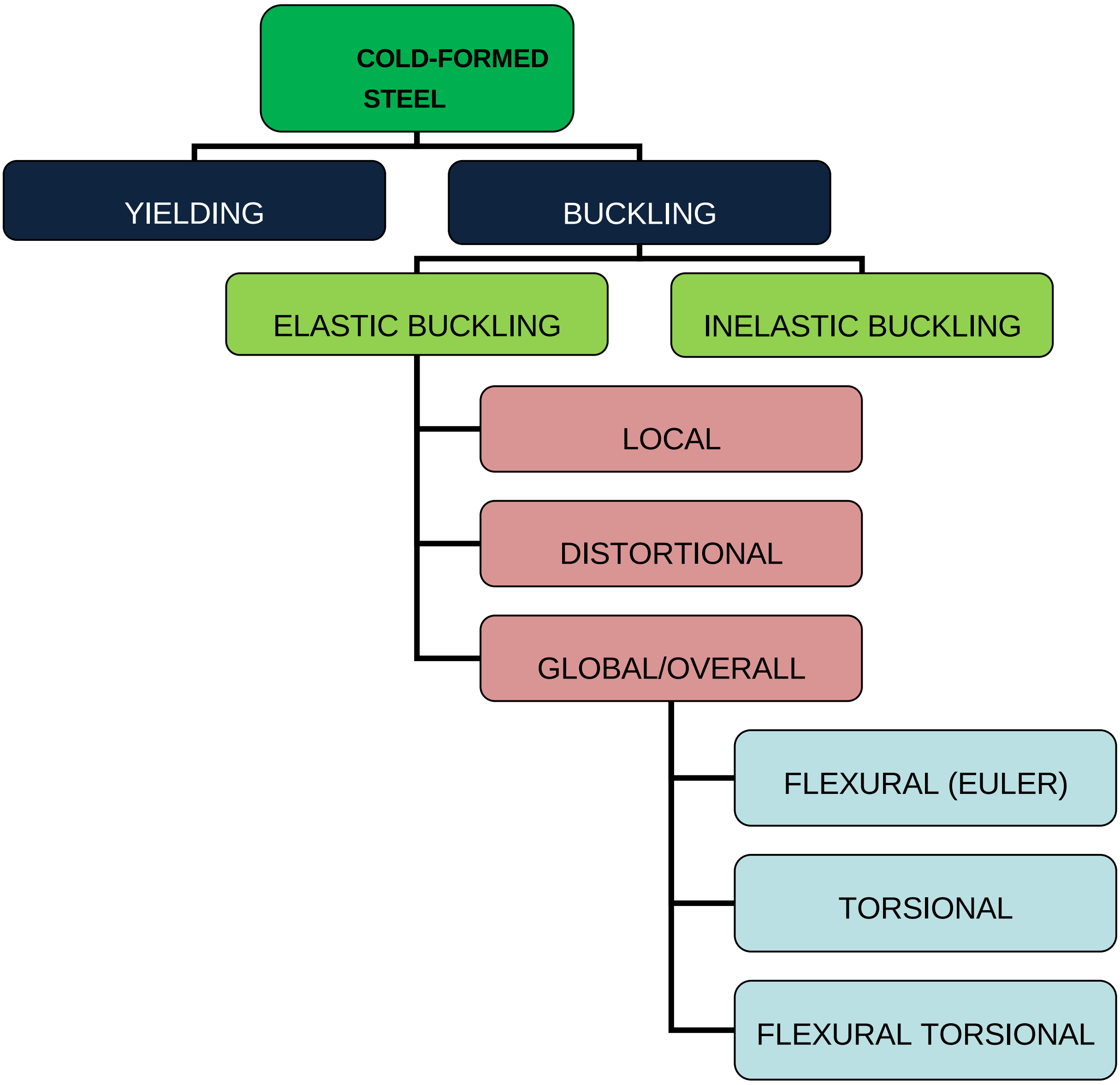
2.1.6 Specific problems of cold formed profiles

For the majority of the situations for cold formed profiles buckling is the main design consideration, member buckling is the most common problem. This is all consequence of the small thickness to width ratio.

Buckling modes that can appear for cold formed steel profiles:

- Local buckling
- Distortional buckling

- Global buckling
    - Flexural
    - Torsional
    - Flexural torsional



2.2 Design procedures

2.2.1 The Direct Strength Method-AISI (2007)

The Direct Strength Method requires determination of the elastic buckling behaviour of the member , and then provides series of nominal strength curves for predicting the member strength based on the elastic buckling behaviour. The procedure does not require effective width calculations or iterations, instead, it uses gross properties and elastic buckling behaviour of the cross section to predict the strength.

2.2.2 Local Buckling via Finite Strip (Mcrl)

Local buckling involves significant distortion of the cross-section, but this distortion involves only rotation, not translation, at the fold lines of the member.

The nominal flexural strength, Mnl, for local buckling shall be calculated in accordance with the following:

For $\lambda_l \leq 0.776$ (1)

$$M_{nl} = M_{ne} \tag{2}$$

For $\lambda_l > 0.776$ (3)

$$M_{nl} = \left(1 - 0.15 * \left(\frac{M_{crl}}{M_{ne}}\right)^{0.4}\right) * \left(\frac{M_{crl}}{M_{ne}}\right)^{0.4} * M_{ne} \tag{4}$$

Where $\lambda_l = \sqrt{M_{ne}/M_{crl}}$ (5)

$$M_{ne} = S_f * F_y \tag{6}$$

S_f - Gross section modulus referenced to the extreme fiber in the first yield

F_y - Yield stress

M_{crl} - Critical elastic local buckling moment determined by analysis

The same calculations can be done with member plastic moment.

For $\lambda_l \leq 0.776$ (7)

$$M_{nl} = M_{pl} \tag{8}$$

For $\lambda_l > 0.776$ (9)

$$M_{nl} = \left(1 - 0.15 * \left(\frac{M_{crl}}{M_{pl}}\right)^{0.4}\right) * \left(\frac{M_{crl}}{M_{pl}}\right)^{0.4} * M_{pl} \tag{10}$$

Where $\lambda_l = \sqrt{M_{pl}/M_{crl}}$ (11)

$$M_{pl} = Z_f * F_y \tag{12}$$

M_{pl} - Member plastic moment

Z_f - Plastic section modulus

2.2.3 Distortional buckling via finite strip (Mcrd)

Distortional buckling involves both translation and rotation at the fold line of a member. Distortional buckling involves distortion of one portion of the cross-section and predominantly rigid response of a second portion.

The nominal flexural strength, Mnd, for distortional buckling shall be calculated in accordance with the following:

For $\lambda_l \leq 0.673$ (13)

$$M_{nd} = M_y \tag{14}$$

For $\lambda_l > 0.673$ (15)

$$M_{nd} = \left(1 - 0.22 * \left(\frac{M_{crd}}{M_y}\right)^{0.5}\right) * \left(\frac{M_{crd}}{M_y}\right)^{0.5} * M_y \quad (16)$$

Where $\lambda_l = \sqrt{M_y/M_{crd}}$ (17)

$$M_y = S_f * F_y \quad (18)$$

S_f - Gross section modulus referenced to the extreme fiber in the first yield

F_y - Yield stress

M_{crd} - Critical elastic distortional buckling moment determined by analysis

The same calculations can be done for the member plastic moment.

For $\lambda_l \leq 0.673$ (19)

$$M_{nd} = M_{pl} \quad (20)$$

For $\lambda_l > 0.673$ (21)

$$M_{nd} = \left(1 - 0.22 * \left(\frac{M_{crd}}{M_{pl}}\right)^{0.5}\right) * \left(\frac{M_{crd}}{M_{pl}}\right)^{0.5} * M_{pl} \quad (22)$$

Where $\lambda_l = \sqrt{M_{pl}/M_{crd}}$ (23)

$$M_{pl} = Z_f * F_y \quad (24)$$

M_{pl} - Member plastic moment

Z_f - Plastic section modulus

2.2.4 Review on the European Approaches

In the project there were 4 type of trapezoidal steel sheets analysed, these sheets had different geometry and thickness, between these sheets were ones with unstiffened and ones with stiffened webs and flanges. During the process multiple parts of the Eurocode-3 were used like: EN 1993-1-5 and EN 1993-1-3.

2.2.4.1 Approach for unstiffened web and flange

For unstiffened web and flange the following approach was applied from EN 1993- -1-5. The effective area of flat compression elements should be obtained using Table.1 for internal elements. The effective area of the compression zone of a plate with the gross cross-sectional area Ac should be obtained from:

$A_{ceff} = \rho * A_c$ where ρ is the reduction factor for plate buckling (25)

The reduction factor ρ may be taken as follows- for internal compression elements:

$$\rho = 1{,}0 \quad \text{for} \quad \lambda_p \leq 0.5 + \sqrt{0.085 - 0.055 * \psi} \tag{26}$$

$$\rho = \frac{\lambda_p - 0.055 * (3 + \psi)}{\lambda_p^2} \leq 1.0 \quad \text{for} \quad \lambda_p > 0.5 + \sqrt{0.085 - 0.055 * \psi} \tag{27}$$

Where

$$\lambda_p = \frac{b/t}{28.4 * \varepsilon * \sqrt{k_\sigma}} \tag{28}$$

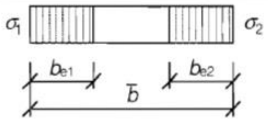
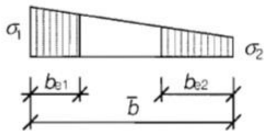
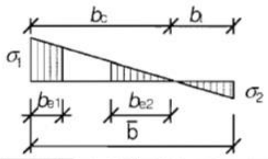
$$\varepsilon = \sqrt{\frac{235}{f_y}} \tag{29}$$

ψ - is the stress ratio

b - is the apropriate width

k_σ - is the buckling factor corresponding to the stress raio and boundary conditions

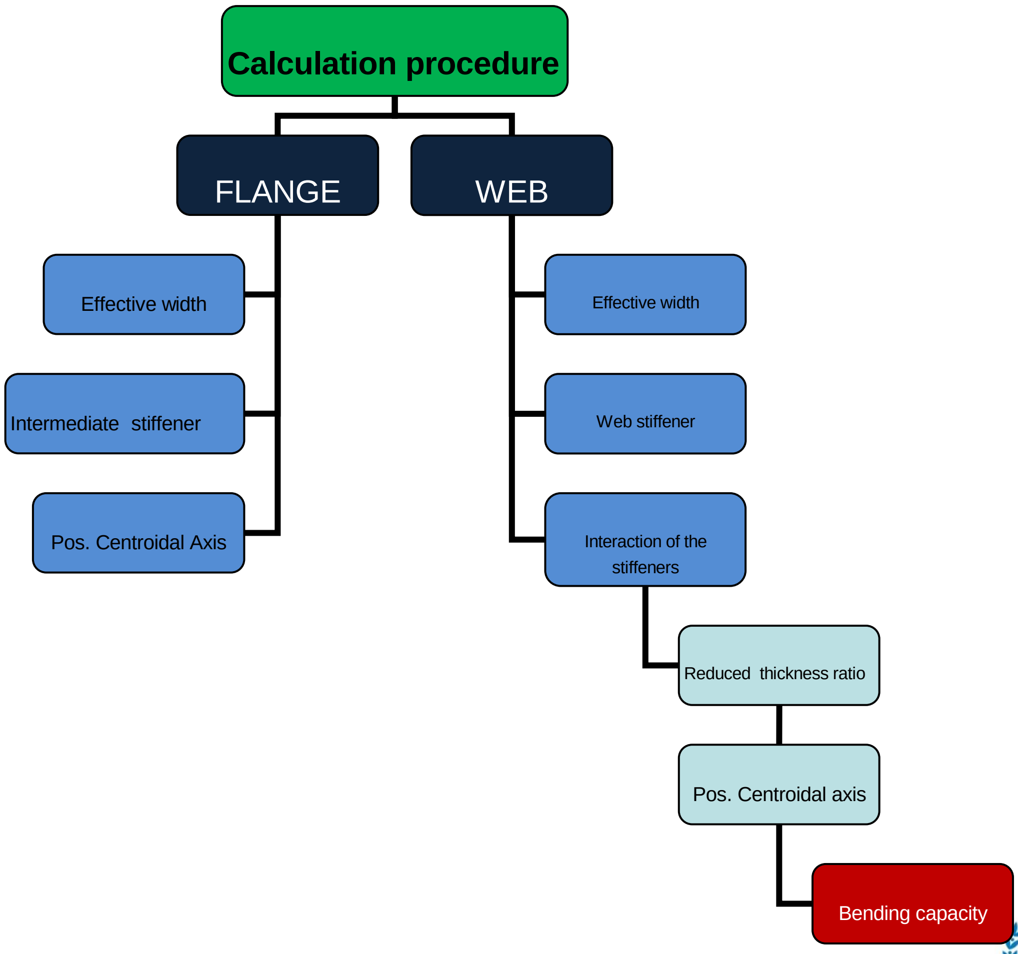
t – is the thickness

Stress distribution (compression positive)	Effective[1)] width b_{eff}
	$\psi = 1$: $b_{eff} = \rho\ \bar{b}$ $b_{e1} = 0{,}5\ b_{eff}$ $\quad b_{e2} = 0{,}5\ b_{eff}$
	$1 > \psi \geq 0$: $b_{eff} = \rho\ \bar{b}$ $b_{e1} = \dfrac{2}{5-\psi} b_{eff}$ $\quad b_{e2} = b_{eff} - b_{e1}$
	$\psi < 0$: $b_{eff} = \rho\ b_c = \rho\ \bar{b} / (1-\psi)$ $b_{e1} = 0{,}4\ b_{eff}$ $\quad b_{e2} = 0{,}6\ b_{eff}$

$\psi = \sigma_2/\sigma_1$	1	$1 > \psi > 0$	0	$0 > \psi > -1$	-1	AC1 $-1 > \psi \geq -3$ AC1
Buckling factor k_σ	4,0	$8{,}2 / (1{,}05 + \psi)$	7,81	$7{,}81 - 6{,}29\psi + 9{,}78\psi^2$	23,9	$5{,}98\ (1 - \psi)^2$

Table.1

2.2.4.2 Approach for flange/web with one, two or multiple stiffeners



For flanges with one, two or multiple stiffeners the following approach was investigated and applied. If the flange is subject to uniform compression, the effective area of the cross-section should be reduced using the parameters presented in Figure.4

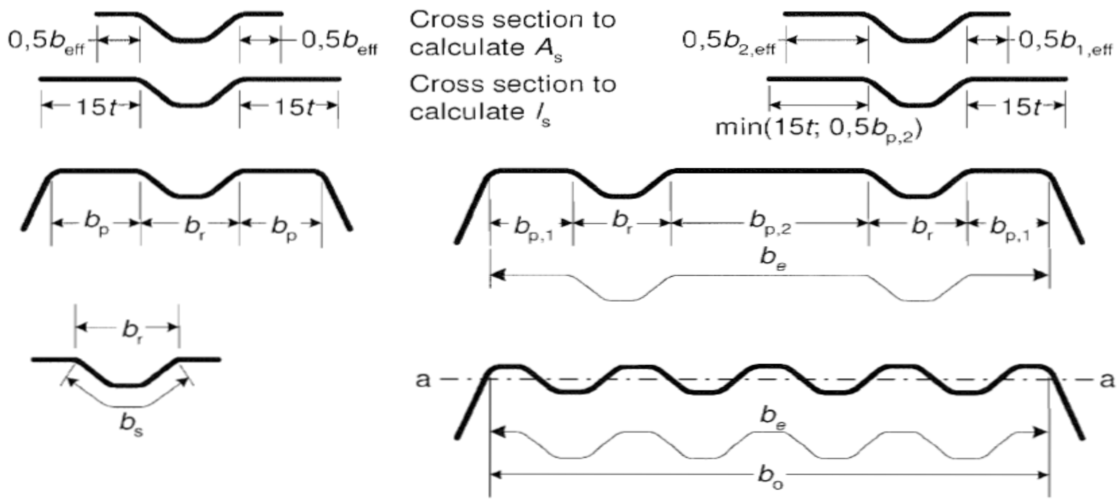


Figure.4

For one central flange stiffener, the following method should be used to determine the elastic critical buckling stress.

$$\sigma_{crs} = \frac{4.2 * k_w * E}{A_s} * \sqrt{\frac{I_s * t^3}{4 * b_p^2 * (2 * b_p + 3 * b_s}} \qquad (30)$$

Where: b_p- is the notional flat width of plane elements shown in Figure.4

b_s- is the stiffener width, measured around the perimeter of the stiffener Figure.4

A_s , I_s - are the cross-section area and the second moment area of the stiffener according to Figure.4

k_w -is a coefficient that allows for partial rotational restraint of the stiffened flange by the other adjacent elements

For two symmetrically placed stiffeners, the elastic critical buckling stress should be calculated as followed.

$$\sigma_{crs} = \frac{4.2 * k_w * E}{A_s} * \sqrt{\frac{I_s * t^3}{8 * b_1^2 * (3 * b_e + 4 * b_1)}} \quad (31)$$

With: $$b_e = 2 * b_{p,1} + b_{p,2} + 2 * b_s \quad (32)$$

$$b_1 = b_{p,1} + 0.5 * b_r \quad (33)$$

Where: $b_{p,1}$ - is the notional flat width of an outer plane element, Figure.4

$b_{p,2}$ - is the notional flat width of the central plane element, Figure.4

b_r - is the overall width of a stiffener, Figure.4

A_s , I_s - are the cross-section area and the second moment area of the stiffener according to Figure.4

For multiple stiffened flange, three or more the effective area of the flange is:

$$A_{eff} = \rho * b_e * t \quad (34)$$

Where ρ is the reduction factor according to EN 1993-1-5, the elastic buckling stress should be calculated as follows:

$$\sigma_{crs} = 1.8 * E * \sqrt{\frac{I_s * t}{b_o^2 * b_e^3}} + 3.6 * \frac{E * t^2}{b_o^2} \quad (35)$$

Where: I_s - is the sum of the second moment of area of the stiffeners about the centroidal axis

b_o - is the width of the flange shown in Figure.4

b_e - is the developed width of the flange shown in Figure.4

The value of kw may be calculated from the compression flange buckling wavelength lb as follows:

-if $l_b/s_w \geq 2$ (36)

$$k_w = k_{wo} \tag{37}$$

-if $l_b/s_w < 2$ (38)

$$k_w = k_{wo} - (k_{wo} - 1) * \left[\frac{2 * l_b}{s_w} - \left(\frac{l_b}{s_w}\right)^2\right] \tag{39}$$

Where sw –is the slant height

The value of lb and kwo may be determined from the following:

-for a compression flange with one intermediate stiffener:

$$l_b = 3.07 * \sqrt[4]{\frac{I_s * b_p^2 * (2 * b_p + 3 * b_s)}{t^3}} \tag{40}$$

$$k_{wo} = \sqrt{\frac{s_w + 2 * b_d}{s_w + 0.5 * b_d}} \tag{41}$$

With: $b_d = 2 * b_p + b_s$ (42)

-for a compression flange with two intermediate stiffeners:

$$l_b = 3.65 * \sqrt[4]{I_s * b_1^2 * (3 * b_e - 4 * b_l)/t^3} \tag{43}$$

$$k_{wo} = \sqrt{\frac{(2 * b_e + s_w) * (3 * b_e - 4 * b_1)}{b_1 * (4 * b_e - 6 * b_1) + s_w * (3 * b_e - 4 * b_1)}} \tag{44}$$

The reduced effective area of the stiffener allowing for distortional buckling should be taken as:

$$A_{sred} = \chi_d * A_s * \frac{f_{yb}/\gamma_{M0}}{\sigma_{com,ser}} \tag{45}$$

The reduction factor χ_d for distortional buckling resistance should be obtained from the relative slenderness:

$$\chi_d = 1.0 \quad \text{if} \quad \lambda_d \leq 0.65 \tag{46}$$

$$\chi_d = 1.47 - 0.723 * \lambda_d \quad \text{if} \quad 0.67 < \lambda_d < 1.38 \tag{47}$$

$$\chi_d = \frac{0.66}{\lambda_d} \quad \text{if} \quad \lambda_d \geq 1.38 \tag{48}$$

Where: $$\lambda_d = \sqrt{f_{yb}/\sigma_{crs}} \tag{49}$$

σ_{crs}- is the elastic critical stress for the stiffener

The effective cross-section of the compression zone of a web should be assumed to consist of the reduced effective areas.

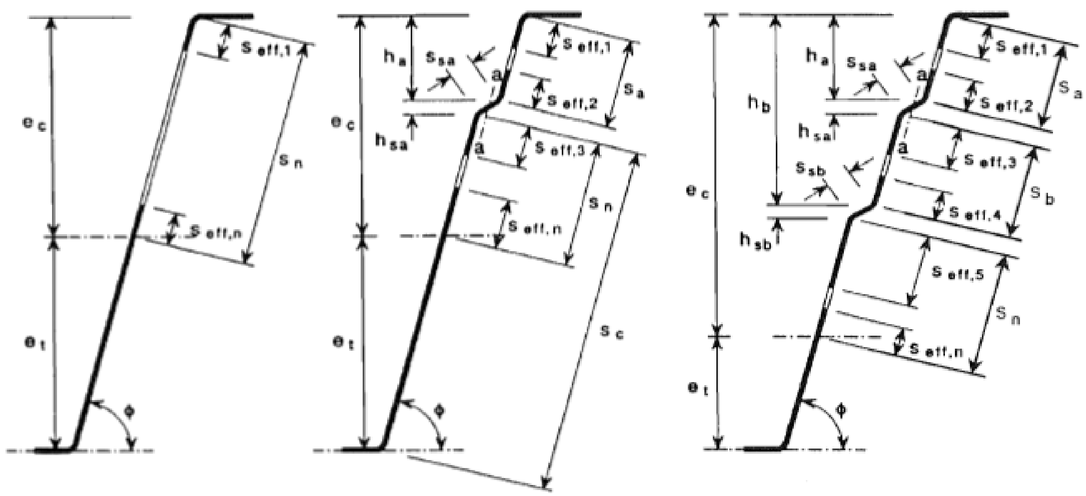


Fig.5 Effective cross-section of webs

The effective areas of the stiffener should be obtained from the following:

-for a single stiffener, or for the stiffener closer to the compression flange;

$$A_{sa} = t * (s_{eff2} + s_{eff3} + s_{sa}) \tag{50}$$

-in which the dimensions are showed in Figure.5

Initially the location of the effective centroidal axis should be based on the effective cross-section of the flanges but the gross-section of the webs. In this case the basic effective width seff0 should be obtained from.

$$s_{eff0} = 0.76 * t * \sqrt{E/(\gamma_{M0} * \sigma_{comEd})} \tag{51}$$

σ_{comEd} - is the stress in the compression flange when the cross-section resistance is reached

If the web is not fully effective, the dimension should be determined as follows:

$$s_{eff1} = s_{eff0} \tag{52}$$

$$s_{eff2} = (1 + 0.5 * h_a/e_c) * s_{eff0} \tag{53}$$

$$s_{eff3} = [1 + 0.5 * (h_a + h_{sa})/e_c] * s_{eff0} \tag{54}$$

$$s_{effn} = 1.5 * s_{eff0} \tag{55}$$

Where: e_c - is the distance from the effective centroidal axis to the system line of the compression flange see Figure.5, and the dimensions are shown in the same figure

If the relevant plane element is fully active the following approach should be used:

-in an unstiffened web is Seff1+Seefn > Sn the entire web is effective:

$$s_{eff1} = 0.4 * s_n \tag{56}$$

$$s_{effn} = 0.6 * s_n \tag{57}$$

-in stiffened web, if Seff1+Seff2 > Sa the whole of Sa is effective:

$$s_{eff1} = \frac{s_a}{2 + 0.5 * h_a/e_c} \tag{58}$$

$$s_{eff2} = s_a * \frac{(1 + 0.5 * h_a/e_c)}{2 + 0.5 * h_a/e_c} \tag{59}$$

-in a web with one stiffener, if Seff3+ Seffn > Seffn the whole of Sn is effective;

$$s_{eff3} = s_n * \frac{[1 + 0.5 * (h_a + h_{sa})/e_c]}{2.5 + 0.5 * (h_a + h_{sa})/e_c} \tag{60}$$

$$s_{effn} = \frac{1.5 * s_n}{2.5 + 0.5 * (h_a + h_{sa})/e_c} \tag{61}$$

For a single stiffener, or for the stiffener closer to the compression flange, the elastic critical buckling stress σ_{crsa} should be determined using:

$$\sigma_{crsa} = \frac{1.05 * k_f * E * \sqrt{I_s * t^3 * s_1}}{A_{sa} * s_2 * (s_1 - s_2)} \tag{62}$$

With: $$s_1 = 0.9 * (s_a + s_{sa} + s_c) \tag{63}$$

$$s_2 = s_1 - s_a - 0.5 * s_{sa} \tag{64}$$

k_f - is a coefficient that allows for partial rotational restraint of the stiffened web by the flanges

I_s - is the second moment area of a stiffener cross-section

s_c - shown in Figure.5

For a single stiffener in compression, or for the stiffener closer to the compression flange in webs with two stiffeners, the reduced effecive area should be determined from:

$$A_{sared} = \frac{\chi_d * A_{sa}}{1 - (h_a + 0.5 * h_{sa})/e_c} \tag{65}$$

Sheeting with flange stiffeners and web stiffeners:

In the case of sheeting with intermediate stiffener in the flange and in the web, interaction between the flexural buckling of the flange stiffenr and the web stiffener should be allowed for by using a modified elastic critical stress σ_{crmod} for both type of stiffeners obtained from:

$$\sigma_{crmod} = \frac{\sigma_{crs}}{\sqrt[4]{1 + \left[\beta_s * \frac{\sigma_{crs}}{\sigma_{crsa}}\right]^4}} \tag{66}$$

Where: σ_{crs}- is the elastic critical buckling stress for an intermediate flange stiffener

σ_{crsa} - is the elastic critical buckling stress for a single web stiffener

$\beta_s = 1 - (h_a + 0.5 * h_{ha})/e_c$ - for a profile in bending (67)

3. Review on the experiment

This paper is elaborated following the data and the results from three experiments that were carried out on three different type of trapezoidal steel sheets H150, H55, EUROCOL 60 at Escola Tecnica Superior d'Enginyeria Industrial de Barcelona. The experiment is a three channel type of test where the converted data contains the ultimate load applied by the hydraulic press and the maximum displacements on the two sides of the trapezoidal steel sheet.

3.1. Test set-up

The test set-up conform EN-1993-1-3 is th following for a single spam test:

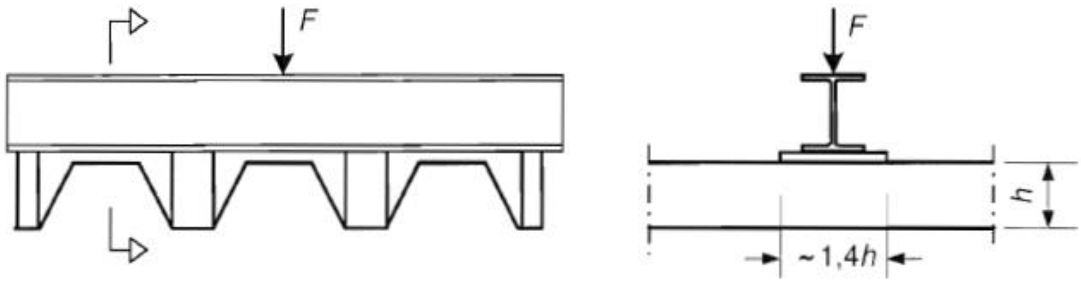


Figure.6 Test set-up for single spam test

This test may be used to determine the moment resistance and rotation capacity of a cross-section. This specimen should have the length of at least 15 times its greatest transversal dimension. The spacing of lateral restraints to the compression flange should not be less than the spacing to be used in service.

A pair of point loads should be applied to the specimen to produce a length under uniform bending moment at midspan of at least 0.2 x span but no more than 0.33 x span. These loads should be applied through the shear center of the cross-section. The section should be torsionally restrained at the load points. If necessary, local buckling of the specimen should be prevented at the points of load application, to ensure that failure occurs within the central portion of the span. The deflection should be measured at the load position, at midspan and at the ends of the specimen.

For the three experiments the following tes set-up was used at Escola Tecnica Superior d'Enginyeria Industrial de Barcelona

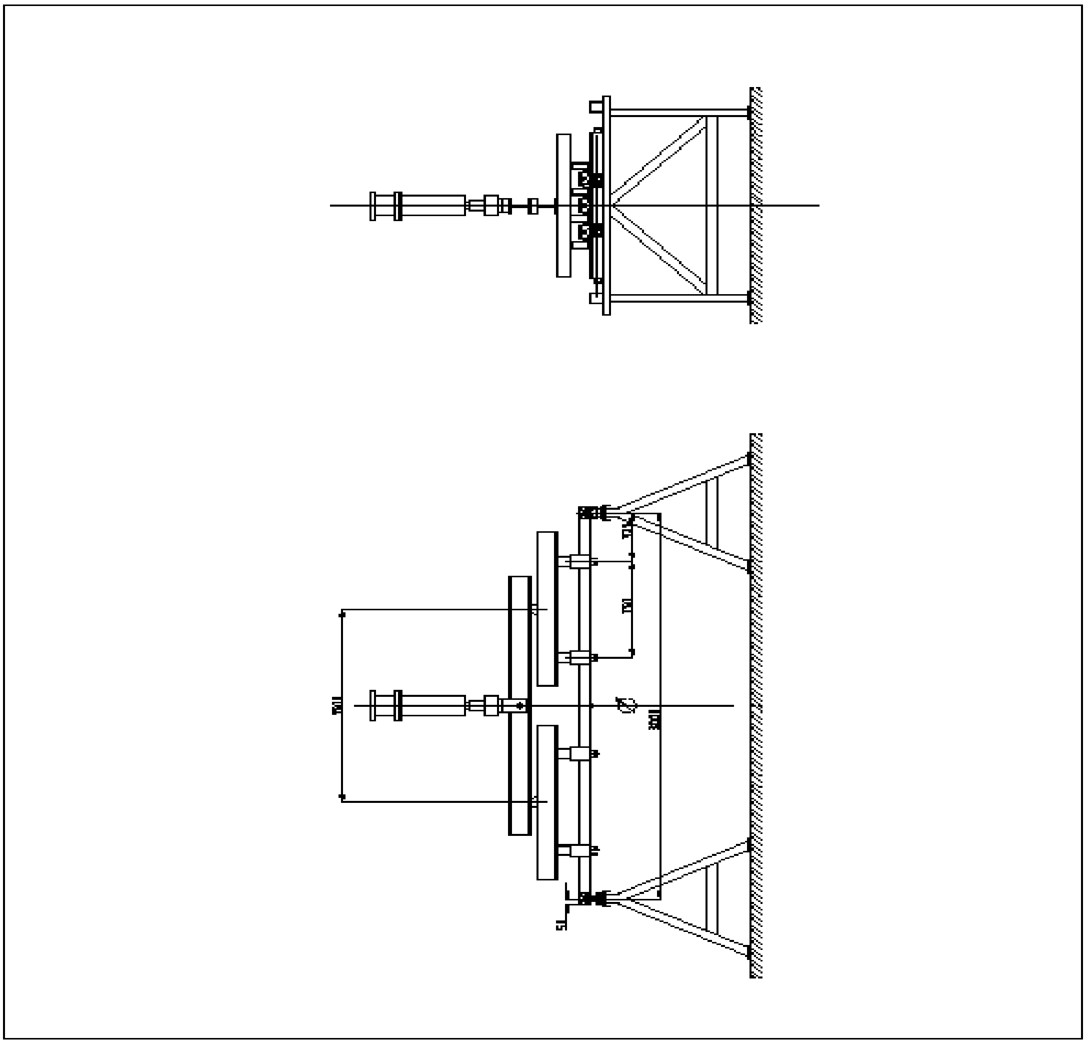


Figure.7 Test set-up

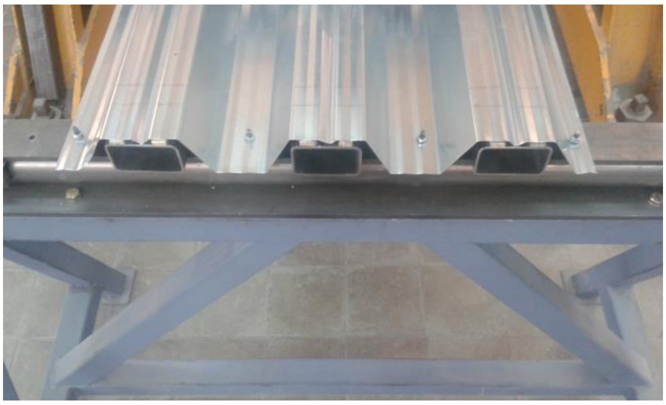
3.2. Real life scaled experiment

The experiment presented in the following chapter is for EUROCOL 60, all the supports, positioning and set-up configuration were desgned for this type of steel sheet. The supports used during the experiment were created from the conditions in EN-1993-1-3, they have the following characteristics 100*60*4, having the length of 100 mm which is exactly 1.4*h.

Where: h – is the height of the sheet

The contact surface between the supports and the sheet is created by the help of wooden elements glued to the supports surface as shown in Figure.8. There were a total of 18 pieces of supports, that were created for the experimental test for EUROCOL 60 steel sheet. There were 6 pieces positioned under the sheet in the two ends of the element, where the constraints existed, 12 other support where positioned on the top of the sheet to help in the force ditribution and to make a good load transmission from the hydraulic jack to the sheet.

Figure.8 Support positioning during the experiment



In the two ends of the steel sheet two elements were created having the role of constraints which had the purpose to allow only movements of rotation in the one end and rotation and translation in the other end. Also under the sheet there were 4 auxiliary profiles mounted to prevent the appearance of bending in the transversal axis of the sheet. It is also for preventing the sheet to deform over this axis not letting it to open. Illustration in Figure.9

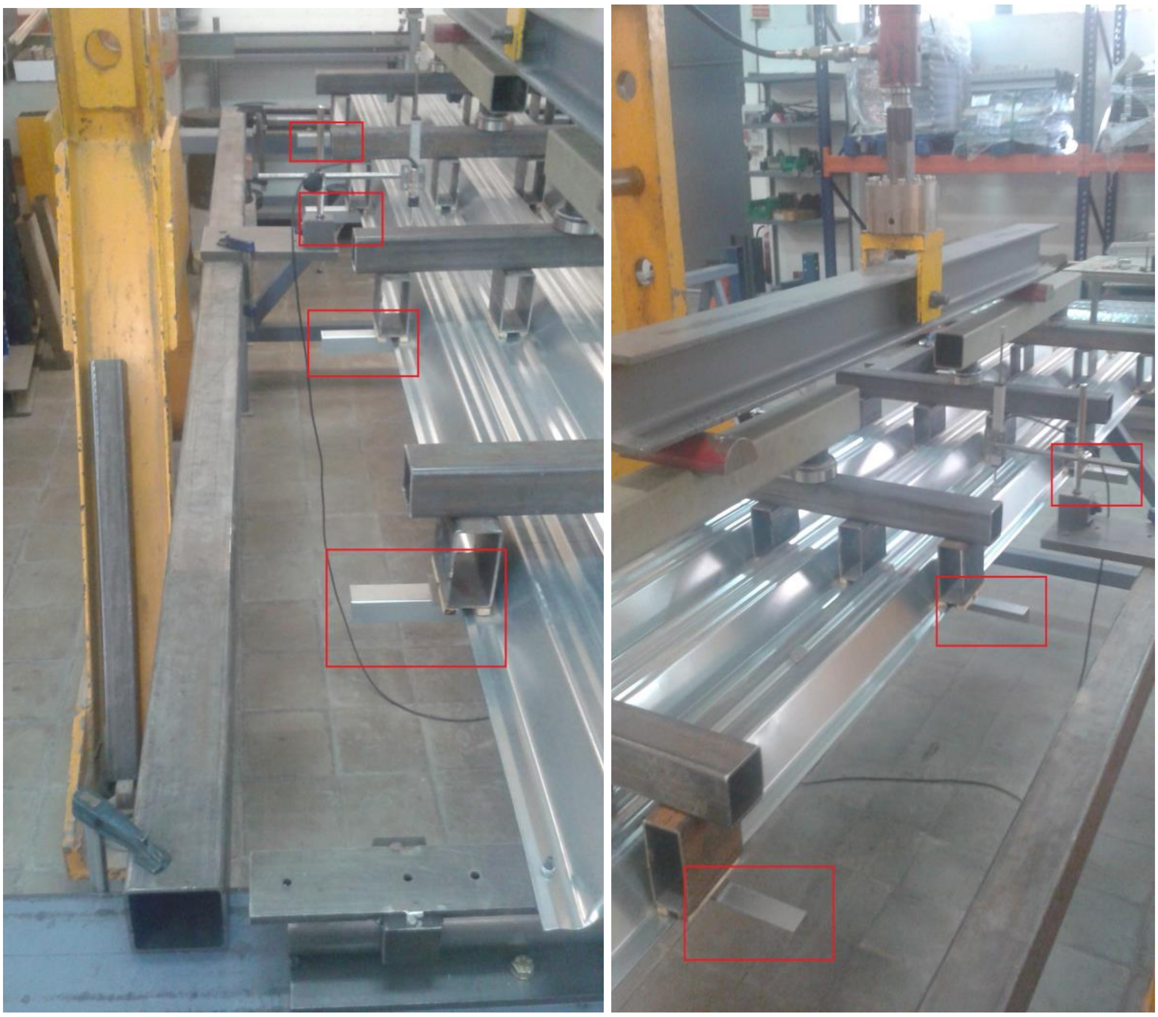


Figure.9 Auxiliary profiles

The first calibration during the set-up was made about the central vertical axis of the hydraulic jack which should be perfectly aligned with the vertical axis of the HE160B steel beam and the centre of the transversal section of the trapezoidal steel sheet as shown in Figure.10

Figure.10 Vertical Axis Calibration

The load transferring system from the hydraulic jack to the steel sheet consist from a HE160B steel beam, two half cylinders that helps to a better distribution of the load to the two profiles which are positioned over the longitudinal axis. Also 4 profiles in the direction of the transversal axis are positioned above the 12 pieces of supports that are in contact with the steel sheet Figure.11. Between the longitudinal and transversal profiles there were 4 elements used which had the form of a half sphere, and it had the possibility to move inside its frame to ensure a better load distribution.

Figure.11 Load transferring system

Before the start of the experiment, the displacement measuring sensors need a calibration, which is realised with the help of a flat surfaced element with all the dimensions known. At the end of the experiment the results from the displacement sensors will be interpreted according to the modifications caused by the calibration. Figure.12

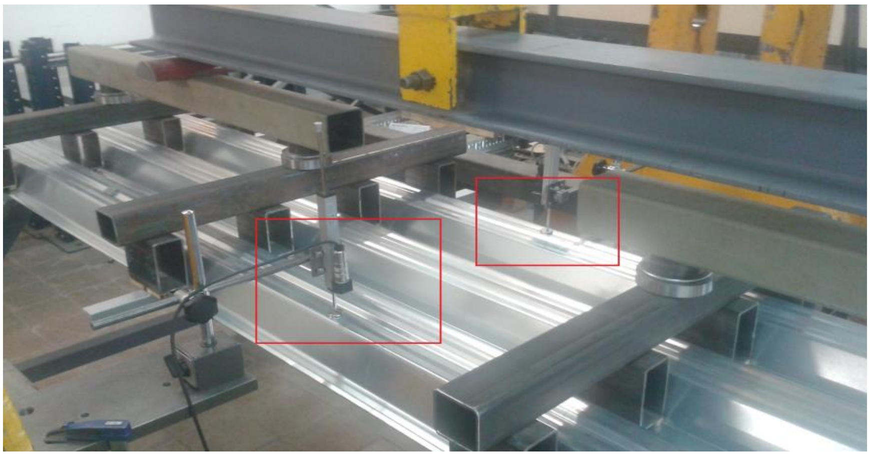


Figure.12

After the experimental test the failure mode is analysed, and the data obtained in the process will be necessary to determine the ultimate bending moment of the sheet. Also the results will be compared with the ones obtained from the FEM method and from the numerical analysis that was carried out. This type of experimental test presented for EUROCOL 60 was carried out for sheet H150 and H55 using the same type of set-up.

Figure.13 The experimental failure mode

4. Software

4.1 CUFSM

CUFSM is a software usually used for thin-walled cold-formed steel elements. In the project it is used to determine the multiplication factor for local and distortional buckling that will be used to calculate the critical bending moments of the 4 sheets that has been investigasted.

4.1.1 Defining the material and the section

In the software interface the section of the sheets is created by using global coordinates, all the material properties are introduced and the constraints on the two sides of the sheets not allowing translation on the x-x axis and rotation about y-y axis.

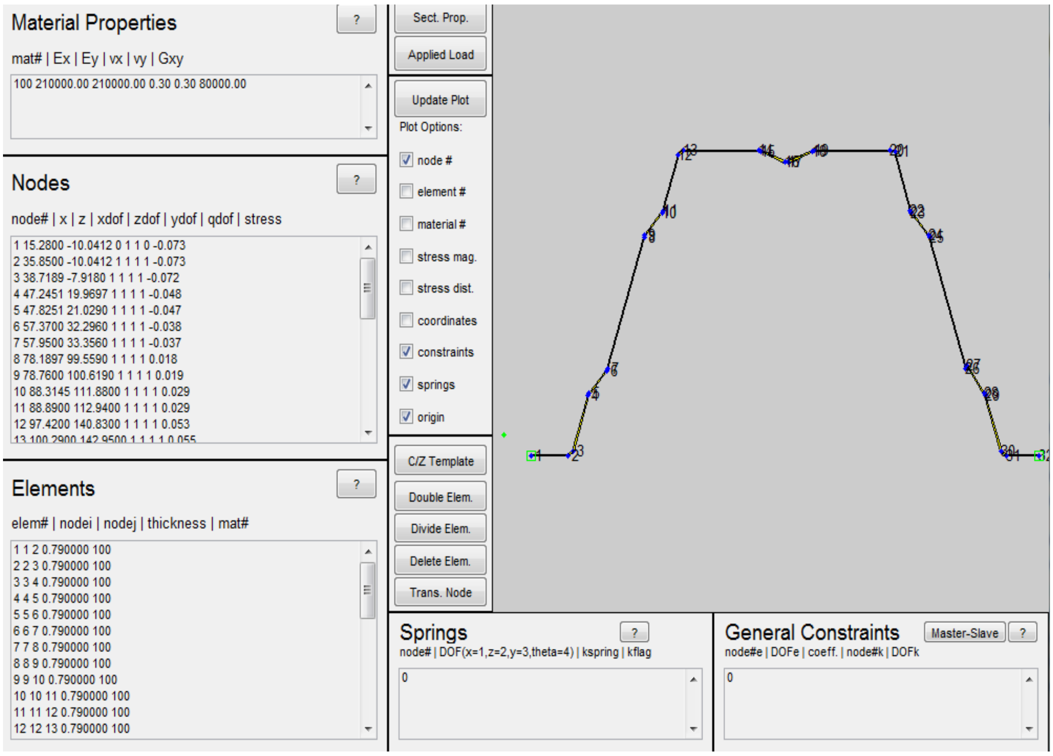


Figure.14 H150

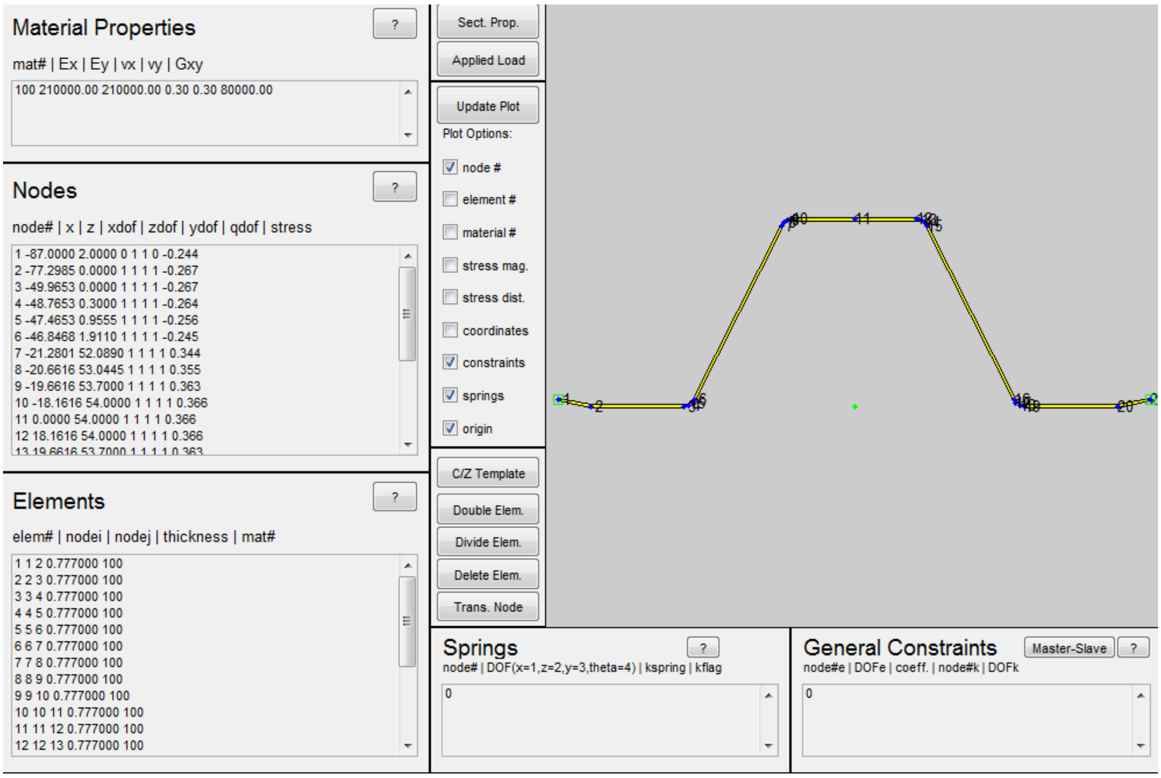


Figure.15 H55

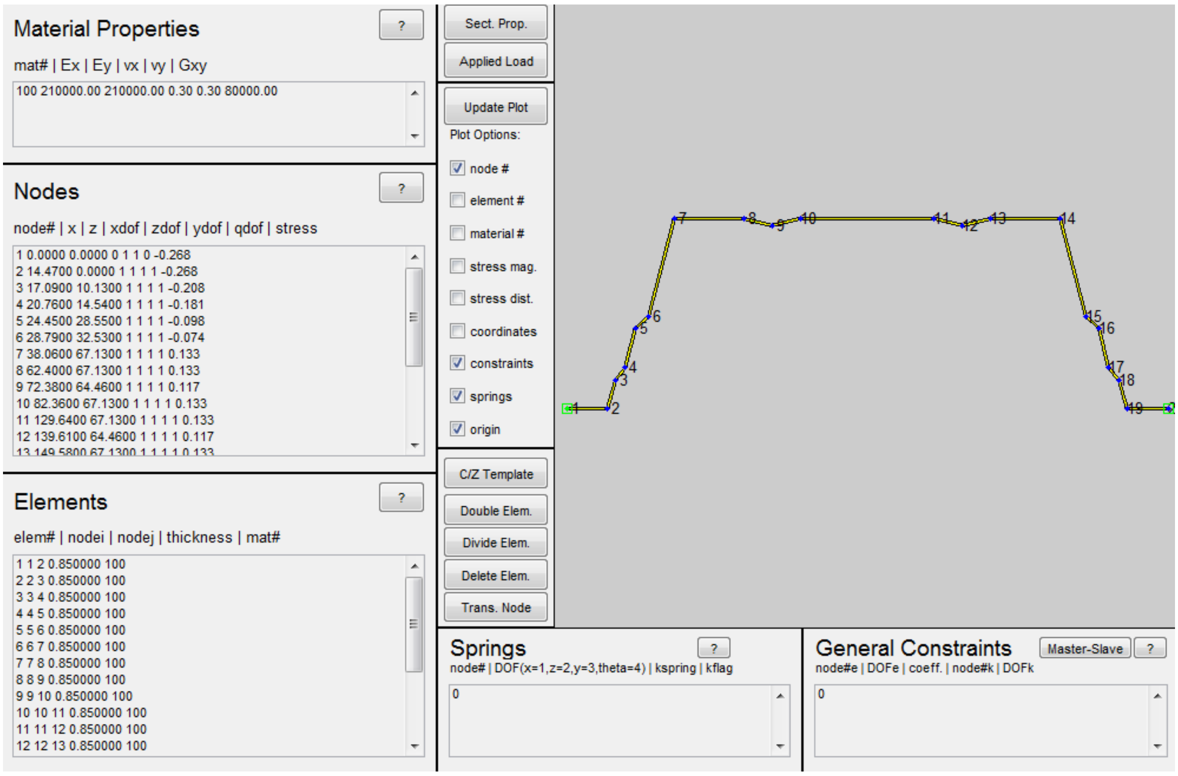


Figure.16 H68

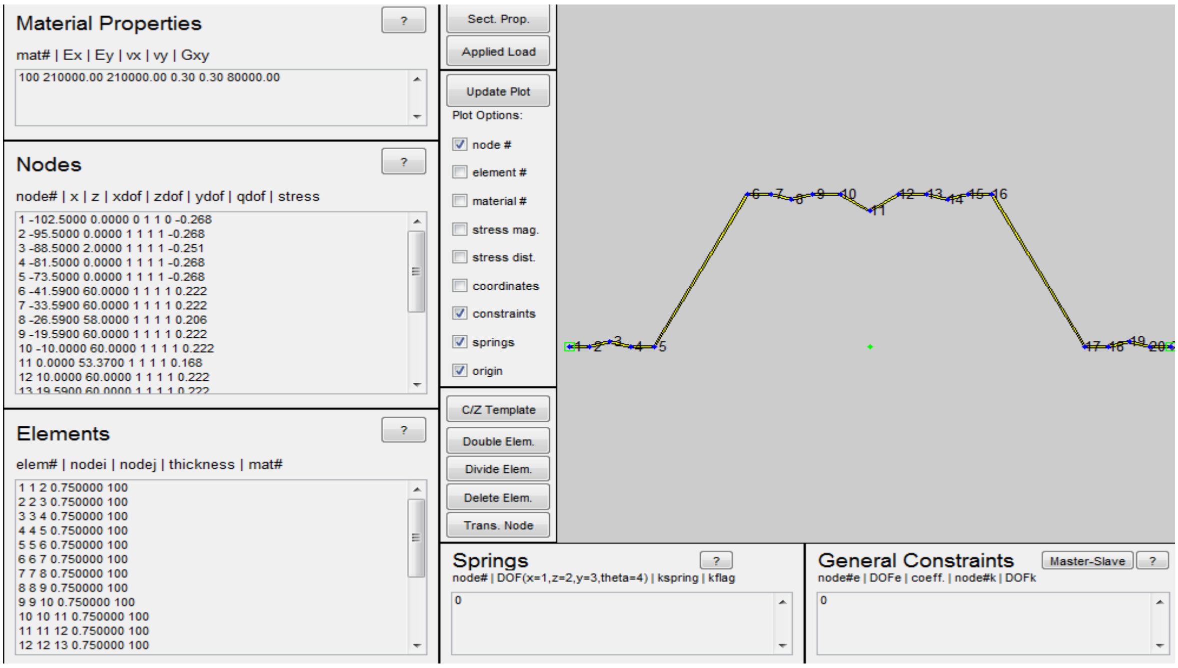


Figure.17 EUROCOL 60

4.1.2 Loads

The applied load/ bending moment is applied in the left side of the interface, on the right side a diagram of stress distribution is shown.

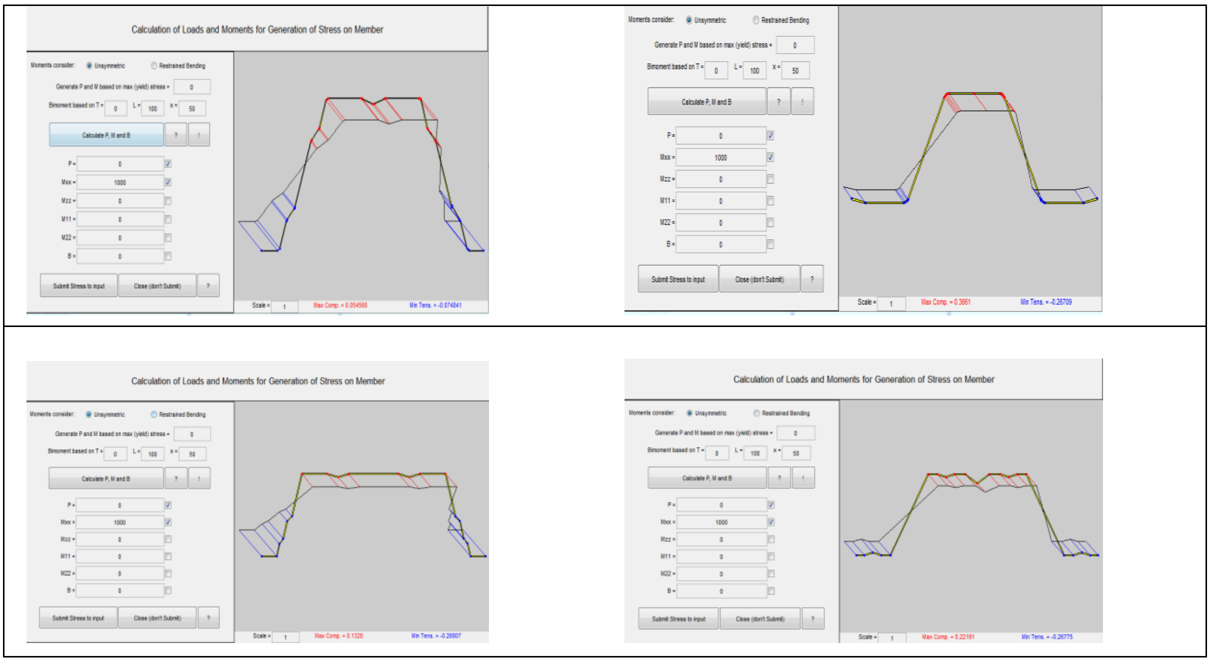


Figure.18

4.1.3 Analysis and results

A buckling analysis was performed to determine the load factor for the critical elastic bending moment for local and distortional buckling. In the interface the buckled shape and the load factor is shown.

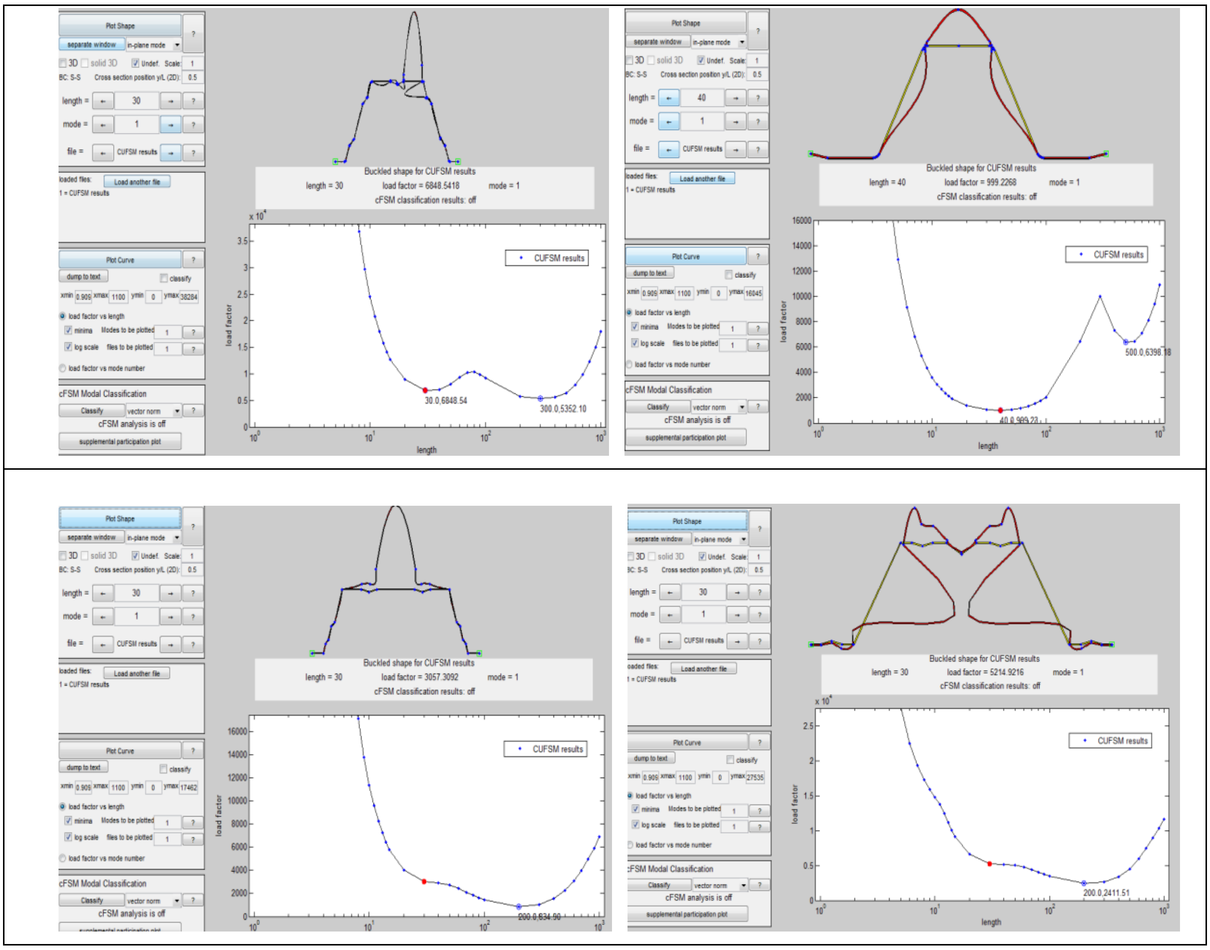


Figure.19 Local buckling, buckled shape

The load factor is used in the numerical analysis by the North-American approach. For sheet H55 the absence of the stiffeners in the web and in the flange concludes in the lack of distortional buckling, that's why sheet H55 is missing from Figure.20.

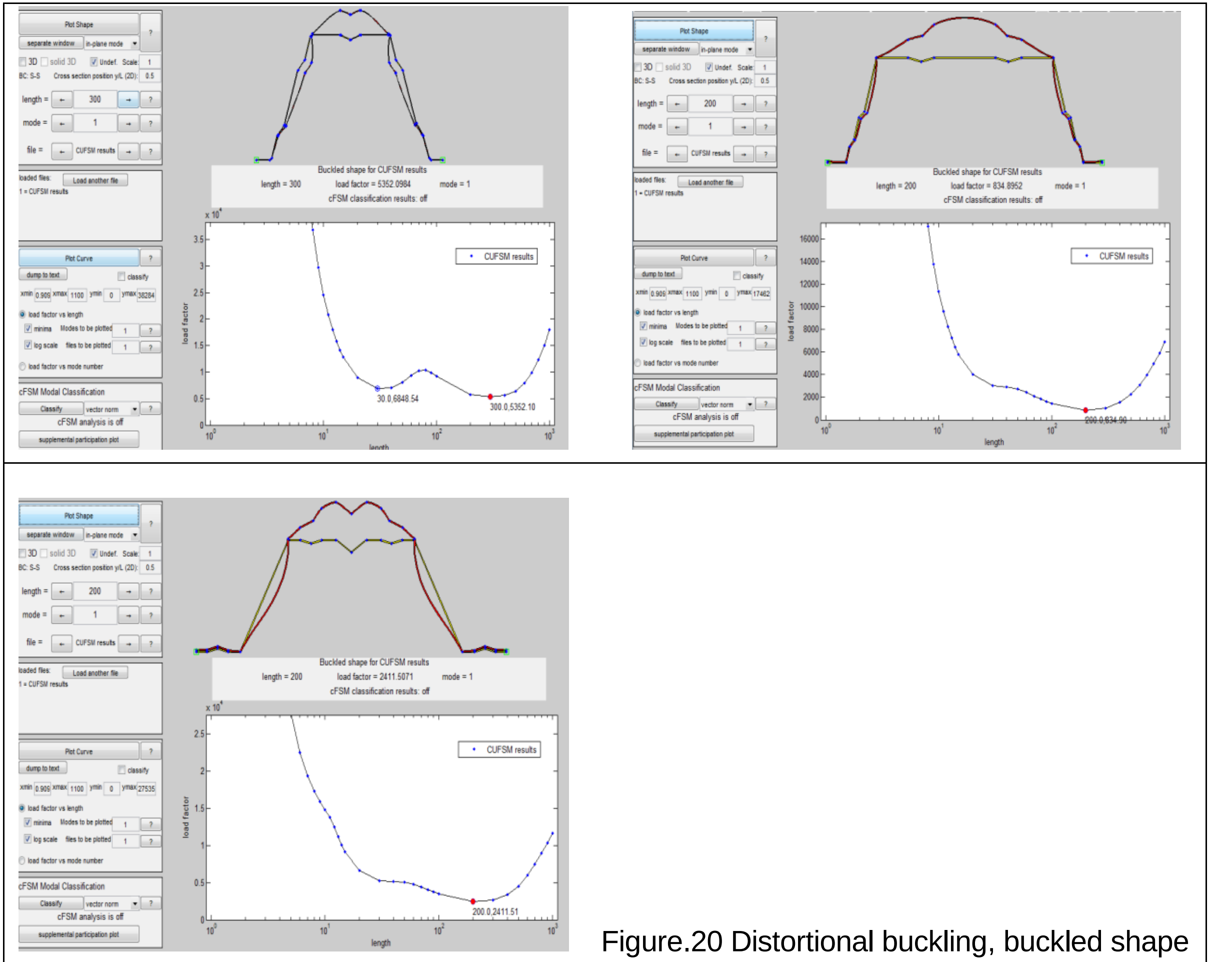


Figure.20 Distortional buckling, buckled shape

4.2 Ansys – Mechanical APDL

Ansys Mechanical APDL is a finite element software used in this paper for determining the ultimate bending moment of the sheet.

4.2.1 Finite element type

SHELL281 is suitable for analysing thin to moderately-thick shell structures. The element has eight nodes with six degrees of freedom at each node: translations in the x,y,z axes, and rotations about the x,y,z axes.

It is well suited for linear, large rotations and large strain non linear applications.

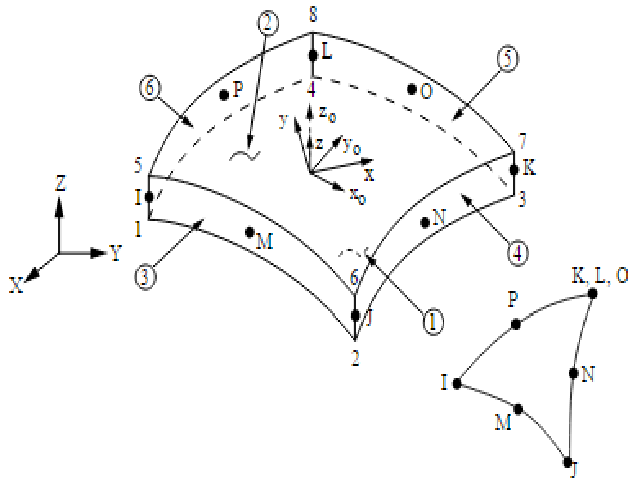


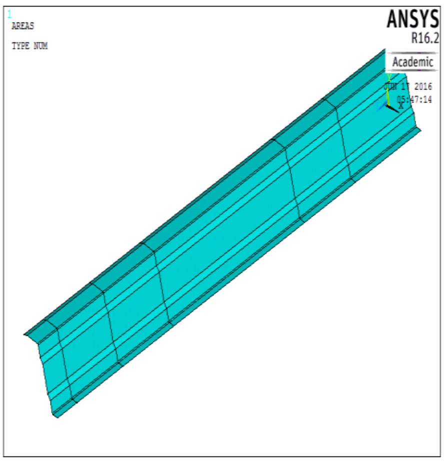
Figure.21 SHELL 281

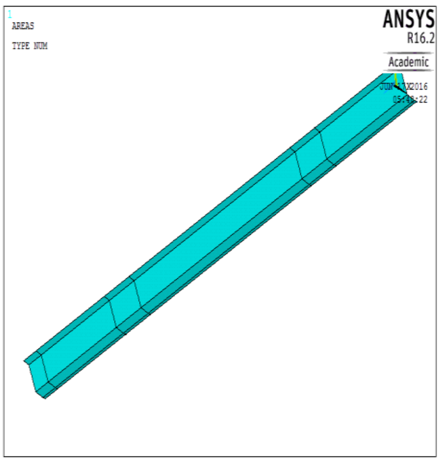
4.2.2 Generating the macros

The macro is a list of command that can be introduced in the interface of the software, it is an easy and efficient way to generate the model, using these types of command gives the user slightly chances to make errors or mistakes.

One general macro is created to generate a half web of a trapezoidal steel sheet, which has a length of 1500 mm. This macro can be used to create all types of steel sheets with different geometry, yield stress, mesh.

A second material is introduced to avoid local deformations and failure modes in the close environment of the loaded area. This material is assigned just to the loaded parts of the sheet and for the end of the sheet where the supports were positioned in the experimental test. Figure.21





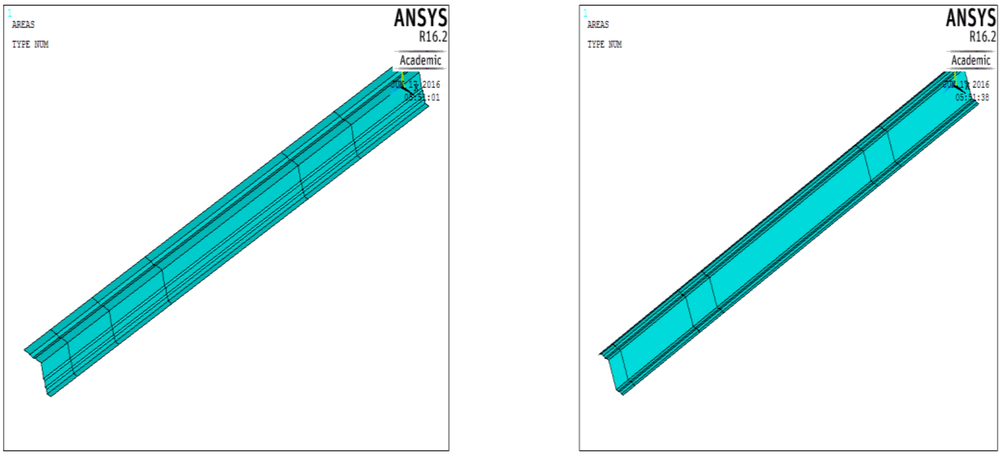


Figure.22 Generating the areas

In the process 3 different sized elements were used in the mesh, the smallest one 5 mm applied in the area where the yielding was suspected and a 15 mm, 30 mm across the sheet shown in Figure.23.

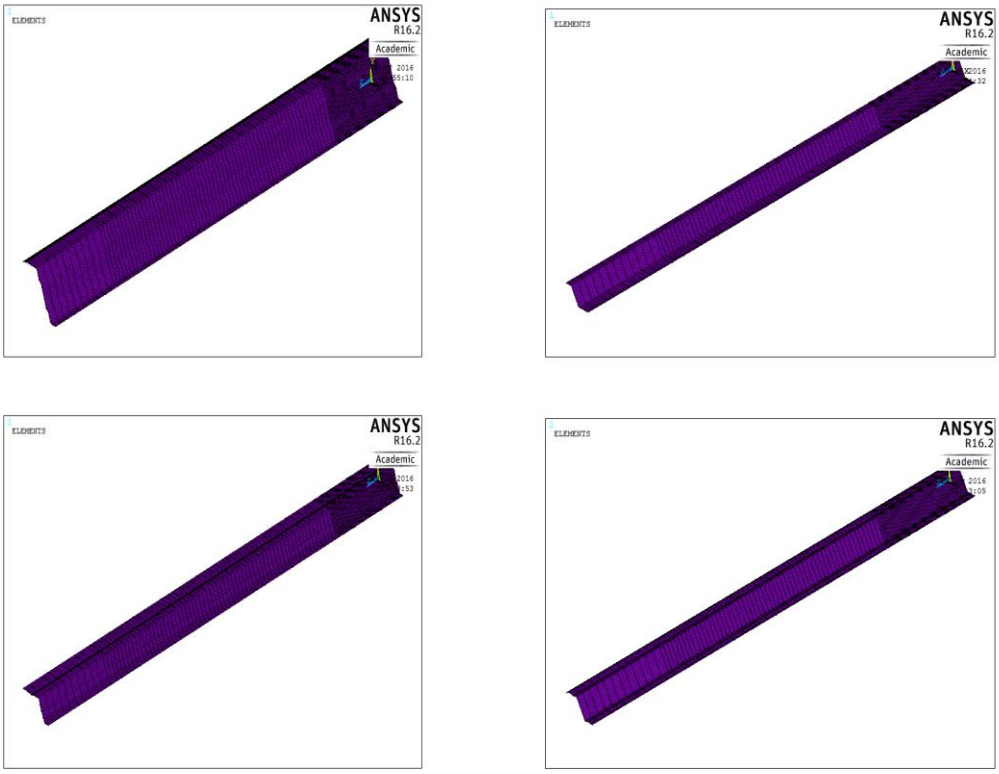


Figure.23 Meshing

There were two types of boundary condition system applied on the sheets. One where for the upper and lower flange and for the middle section of the sheet constraints were applied in direction of the vertical and horizontal axis to simulate the continuity of the sheet. In the end section to model the effect of the supports a constraint was added to the lower flange in the direction of the vertical axis. The second type was applied just for sheet H 150, H 55 and the difference is in the end section where another constraint is applied in the top flange in direction of the vertical axis.

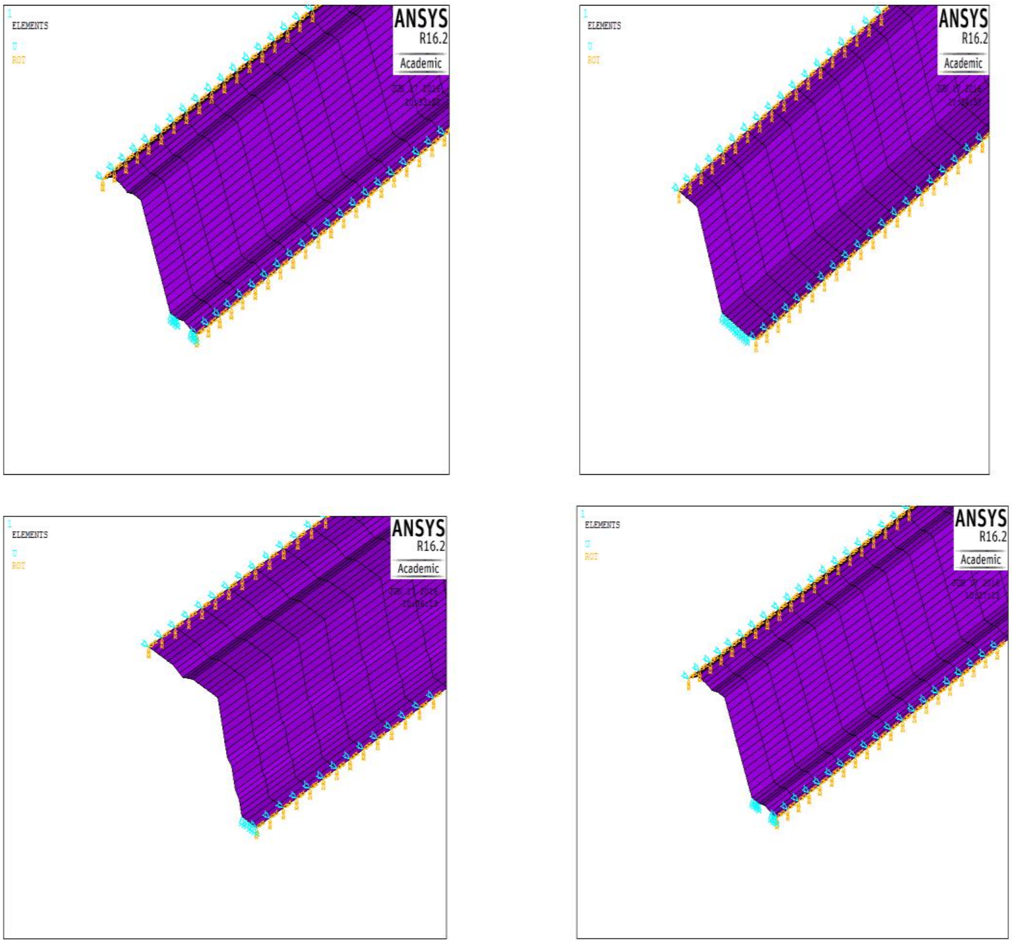


Figure.24 B.c. type I

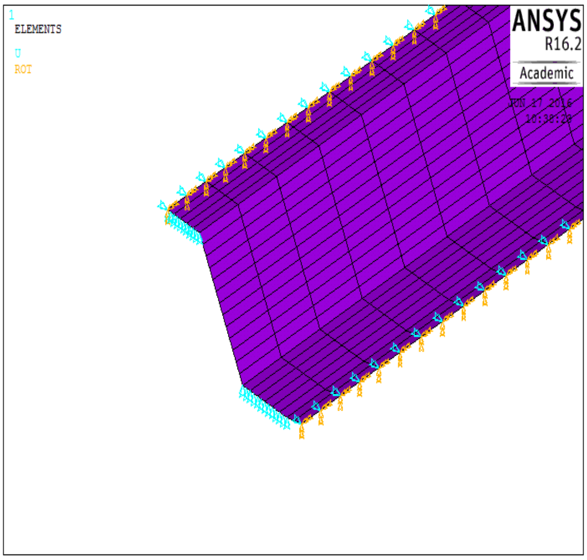


Figure.25. B.c. type II

The load is applied conform the test set-up that was presented earlier in the paper, just to the lower flange of the sheet because only a half web is generated in the software. This type of configuration helps the user to determine the positive bending moment of the sheet. The load is applied just on the surface of the second type of material generated in the macro.

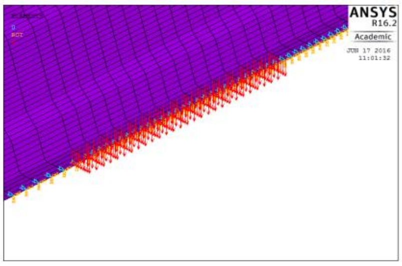


Figure.26

4.2.3 Analysis

After the model is generated a static analysis is made with the pre stressed effect taken in consideration, an eigen buckling analysis follows to determine the displacement in the vertical axis and the buckling modes that appear in the sheet. In Figure.27 the buckling modes and the values of the displacement are shown.

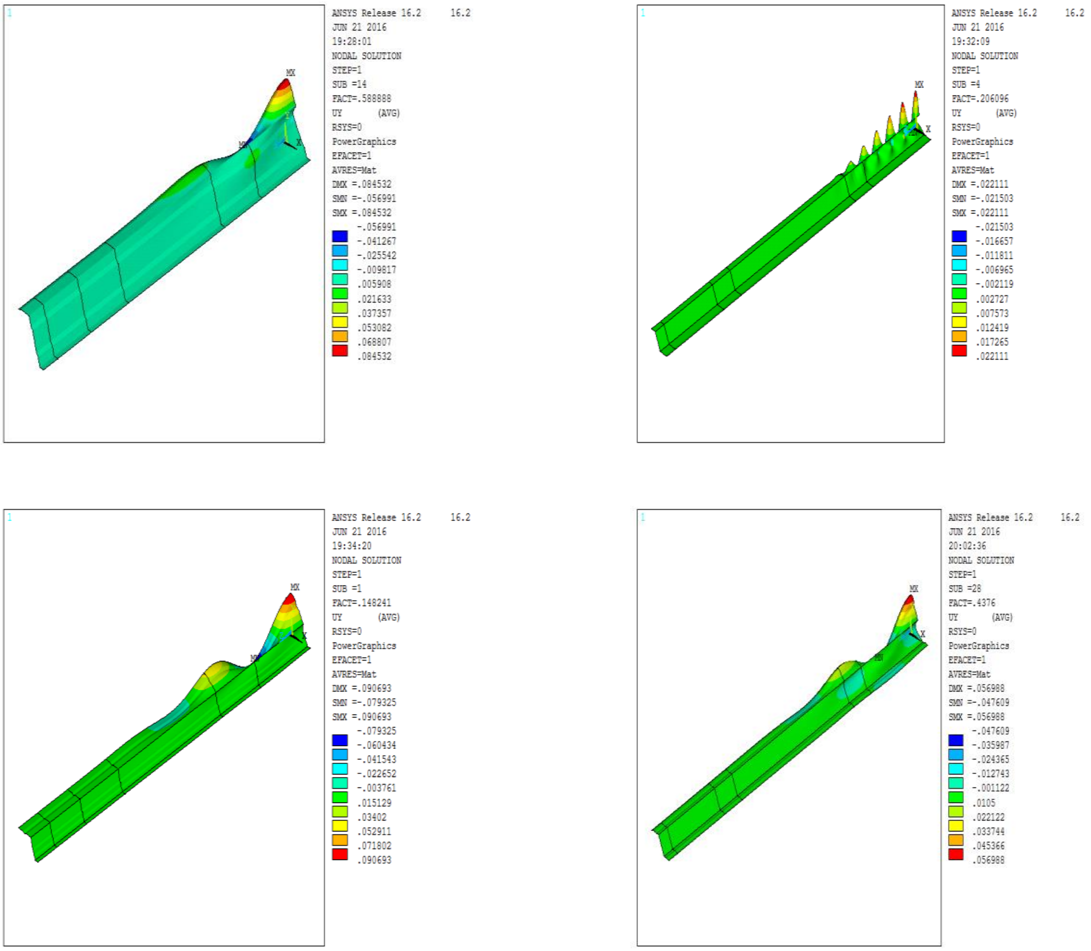


Figure.27 Vertical displacement after the eigen buckling analysis

In the last part of the FEM research a non linear analysis is carried out. For the non linear analysis its necessary to introduce an imperfection and to update the geometry of the model. The imperfection is determined from the vertical displacement obtained from the eigen buckling analysis results and from the following ratio:

$$e_0 = b/200 \tag{68}$$

$$e_0 = b/150 \tag{69}$$

The non linear analysis is using the Arc-length technique. The yielding of the sheets appear in the expected zone for all 4 types shown in Figure.28

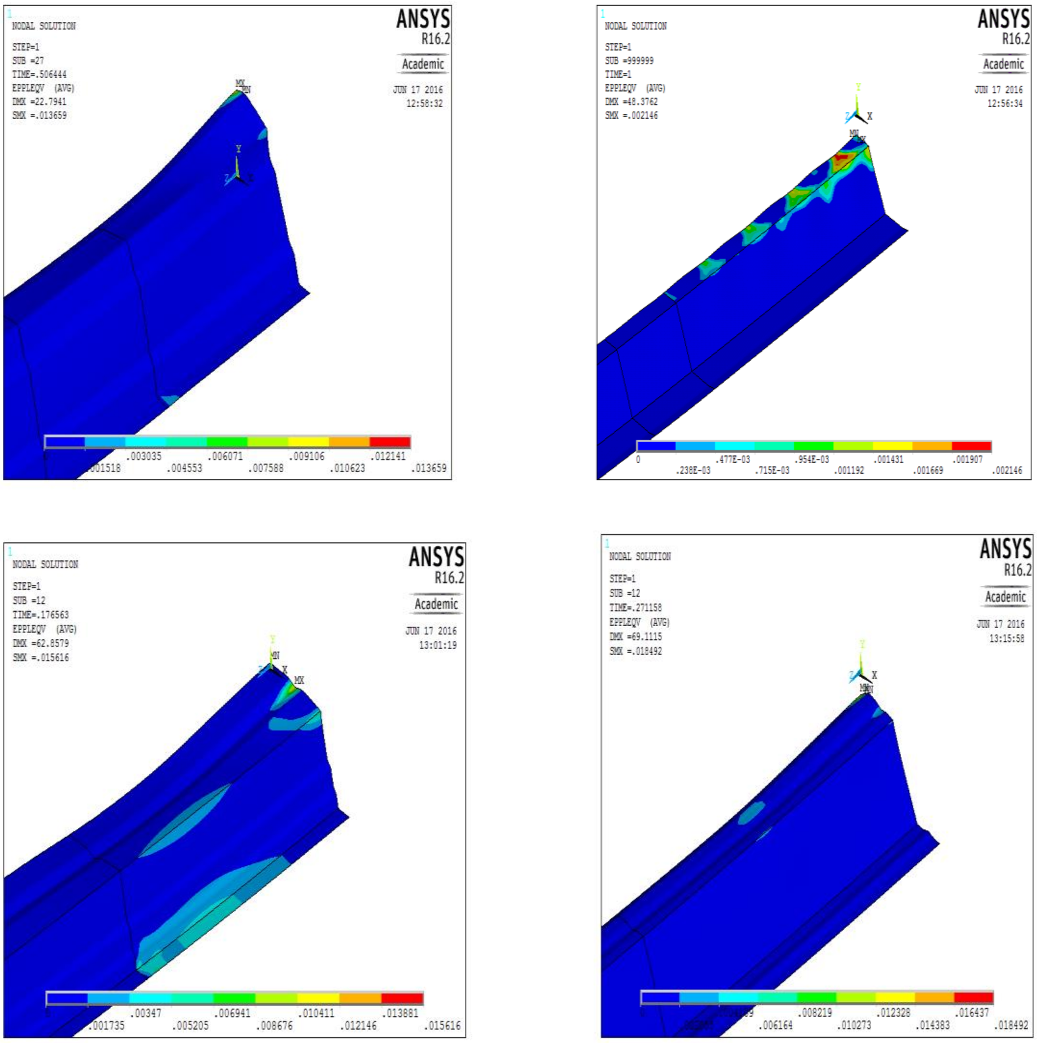


Figure.28 Plastic strain in all 4 types of sheets

From the non linear analysis the reaction solutions in the end of the sheet can be determined, using these results the user can easily determine the ultimate bending moment.

5. Numerical investigations and results

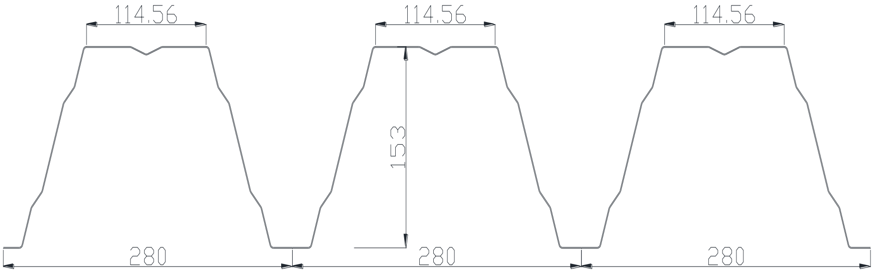
5.1 Introduction

In the project two numerical investigations were carried out, one according to the North-American approaches using the Direct Strength method and the Finite Strip method, and the other one following the European standards and approach. The calculations were carried out for all 4 types of sheet. The results obtained from the numerical investigations were compared with the FEM results and with the experimental tests. During the numerical investigations all the necessary data for the calculation methods were used from prior experimental tests.

5.3 Example of the calculation method using AISI for H150

Design of Cold-Formed Steel Structural Members Using the
Direct Strength Method (AISI-S100-Appendix 1)

Sheet N1:



Local Buckling (1.2.2.2)

The nominal flexural strength, M_{nl}, for local buckling should be calculated accordingly to:

$M_{ne} := S_f \cdot F_y$

$I_{xx} := 1172099.49 mm^4$ values taken from CUFSM

$z_{cg} := 88.7768 mm$ values taken from CUFSM

$$S_f := \frac{I_{xx}}{z_{cg}} = 1.32 \times 10^4 \cdot mm^3$$

$$F_y := 327.81 \frac{N}{mm^2}$$

$$M_{ne} := S_f \cdot F_y = 4.328 \times 10^6 \cdot N \cdot mm$$

$$M_{crl} := 10006848 N \cdot mm = 6.848 \times 10^6 \cdot N \cdot mm$$

$$\lambda_l := \sqrt{\frac{M_{ne}}{M_{crl}}} = 0.795 \qquad \text{(Eq.1.2.2.7)}$$

For $\lambda_l > 0.776$

$$M_{nl} := \left[1 - 0.15\left(\frac{M_{crl}}{M_{ne}}\right)^{0.4}\right]\cdot\left(\frac{M_{crl}}{M_{ne}}\right)^{0.4}\cdot M_{ne} = 4.263\times 10^{6}\cdot N\cdot mm \qquad \text{(Eq.1.2.2.6)}$$

S_f - Gross section modulus referenced to the extreme fiber in the first yield

F_y - Yield stress

M_{crl} - Critical elastic local buckling

Distorsional Buckling (1.2.2.3)

The nominal flexural strength, M_{nd}, for distortional buckling should be calculated accordingly to:

$$M_{crd} := 1000\,5352\cdot N\cdot mm = 5.352\times 10^{6}\cdot N\cdot mm$$

$$M_y := M_{ne} = 4.328\times 10^{6}\cdot N\cdot mm$$

$$\lambda_d := \sqrt{\frac{M_y}{M_{crd}}} = 0.899 \qquad \text{(Eq.1.2.2.10)}$$

For $\lambda_d > 0.673$

$$M_{nd} := \left[1 - 0.22\left(\frac{M_{crd}}{M_y}\right)^{0.5}\right]\cdot\left(\frac{M_{crd}}{M_y}\right)^{0.5}\cdot M_y = 3.635\times 10^{6}\cdot N\cdot mm \qquad \text{(Eq.1.2.2.9)}$$

M_{crd} - Critical elastic local buckling

The ultimate bending moment should be chosen, from the minimum between, the nominal flexural strength for local, distortional buckling:

$$M_{fin} := \min(M_{nd}, M_{nl})$$

$$M_{fin} = 3.635\times 10^{6}\cdot N\cdot mm$$

The ultimate bending moment for the whole sheet, with three webs:

$$M_{Sheet} := 3\cdot M_{fin} = 1.091\times 10^{7}\cdot N\cdot mm$$

$$M_{exp} := 14226750\,N\cdot mm$$

$$P_{\%} := M_{Sheet}\cdot\frac{100}{M_{exp}} = 76.66 \quad \%$$

Using the member plastic moment for the following calculations:

Local Buckling (1.2.2.2)

The nominal flexural strength, M_{nl}, for local buckling should be calculated accordingly to:

$$M_{pl} := Z_f\cdot F_y$$

$$Z_f := 17886.46\,mm^3$$

$$F_y := 327.81\frac{N}{mm^2}$$

$$M_{pl} := Z_f\cdot F_y = 5.863\times 10^6\cdot N\cdot mm$$

$$M_{crl} := 10006848\,N\cdot mm = 6.848\times 10^6\cdot N\cdot mm$$

$$\lambda_l := \sqrt{\frac{M_{pl}}{M_{crl}}} = 0.925 \qquad \text{(Eq.1.2.2.7)}$$

For $\lambda_l > 0.776$

$$M_{nl} := \left[1 - 0.15\left(\frac{M_{crl}}{M_{pl}}\right)^{0.4}\right]\cdot\left(\frac{M_{crl}}{M_{pl}}\right)^{0.4}\cdot M_{pl} = 5.243\times 10^6\cdot N\cdot mm \qquad \text{(Eq.1.2.2.6)}$$

F_y - Yield stress
M_{crl} - Critical elastic local buckling
M_{pl} - Member plastic moment
Z_f - Plastic section modulus

Distorsional Buckling (1.2.2.3)

The nominal flexural strength, M_{nd}, for distortional buckling should be calculated accordingly to:

$$M_{crd} := 10005352\,N\cdot mm = 5.352\times 10^6\cdot N\cdot mm$$

Sheeting with stiffeners in flange and web

$M_y := M_{pl} = 5.863\times 10^{6}\cdot N\cdot mm$

$$\lambda_d := \sqrt{\frac{M_y}{M_{crd}}} = 1.047 \qquad \text{(Eq.1.2.2.10)}$$

For $\lambda_d > 0.673$

$$M_{nd} := \left[1 - 0.22\left(\frac{M_{crd}}{M_y}\right)^{0.5}\right]\cdot\left(\frac{M_{crd}}{M_y}\right)^{0.5}\cdot M_y = 4.424\times 10^{6}\cdot N\cdot mm \qquad \text{(Eq.1.2.2.9)}$$

M_{crd} - Critical elastic local buckling

M_{pl} - Member plastic moment

Z_f - Plastic section modulus

The ultimate bending moment should be chosen, from the minimum between, the nominal flexural strength for local, distortional buckling:

$M_{fin} := \min(M_{nd}, M_{nl})$

$M_{fin} = 4.424\times 10^{6}\cdot N\cdot mm$

The ultimate bending moment for the whole sheet, with three webs:

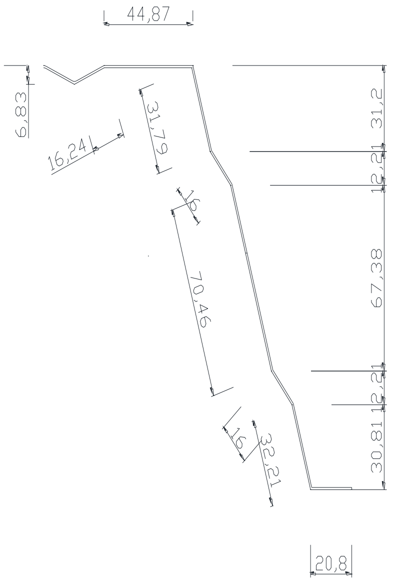
$M_{Sheet} := 3\cdot M_{fin} = 1.327\times 10^{7}\cdot N\cdot mm$

$M_{exp} := 14226750\,N\cdot mm$

$$P_{\%} := M_{Sheet}\cdot\frac{100}{M_{exp}} = 93.298 \quad \%$$

5.3 Example of the calculation method using EN-1993 for H-150

Bending moment capacity of a sheeting with stiffeners in flange and web.



Cross-section to be calculated.

Values of symbols

$$E := 210000 \cdot \frac{N}{mm^2}$$

$$f_y := 327.81 \cdot \frac{N}{mm^2}$$

$$f_{yb} := f_y$$

$$t := 0.79 \cdot mm$$

$$r := 3 \cdot mm$$

$$b_p := 44.87 \cdot mm$$

$$\frac{r}{t} = 3.797 \qquad \frac{r}{t} < 5 = 1$$

$$\frac{r}{b_p} = 0.067 \qquad \frac{r}{b_p} < 0.10 = 1$$

Acording to clause 5.1(3) the influence of rounded corners may be neglected

Top flange

Effective width of part of the top flange (see 4.4 of EN 1993-1-5)

$$b_1 := \frac{b_p}{t} = 56.797$$

$$\varepsilon := \sqrt{\frac{235}{327.81}} = 0.847$$

With k.σ assumed:4

$$k_\sigma := 4$$

$$\lambda_p := \frac{b_1}{28.4 \cdot \varepsilon \cdot \sqrt{k_\sigma}} = 1.181$$

$\psi := 1$ for $k_\sigma := 4$

$$\rho := \frac{\lambda_p - 0.055 \cdot (3 + \psi)}{\lambda_p^{\,2}} = 0.689 \qquad (4.2)$$

$$b_{e1} := 0.5 \cdot 0.689 \cdot 44.87 \cdot mm = 15.458\,mm$$

$$b_{e2} := b_{e1} = 15.458\,mm$$

Intermediate stiffener (see clause 5.5.3.4.2)

For caculations of As:0.5be=15.458mm

For calculation of Is:15t=15*0.79=11.85mm

	I	z	Iz	Iz^2	h	$\frac{Ih^2}{12}$
	23.7	0	0	0	0	0
	32.48	3.02	98.08	296.2	6.83	126.2
Sum	56.18		98.08	296.2		

$$z := \frac{98.08 \cdot mm^2}{56.18 \cdot mm} = 1.746 \cdot mm$$

$$A_{s1} := 2 \cdot 15.458\,mm + 32.48\,mm = 63.396\,mm \qquad \frac{A_s}{t}$$

$$b_p := 44.87 \cdot mm$$

$$b_s := 2 \cdot 16.24\,mm = 32.48\,mm$$

$I_s := 170.36mm^4$ value taken from CUFSM

$$I_{s1} := \frac{I_s}{t} = 215.646mm^3$$

The values of lb and kwo may be determined from the following:
-for a compression flange with one intermediate stiffener:

$$l_b := 3.07 \cdot \sqrt[4]{I_s \cdot b_p^2 \cdot \frac{(2 \cdot b_p + 3 \cdot b_s)}{t^3}} \qquad (5.25)$$

$$k_{wo} := \sqrt{\frac{s_w + 2 \cdot b_d}{s_w + 0.5 \cdot b_d}} \qquad (5.26)$$

$$l_b := 3.07 \cdot \left[215.646mm^3 \cdot 0.79 \cdot mm \cdot 44.87^2 \cdot mm^2 \cdot \frac{(2 \cdot 44.87 \cdot mm + 3 \cdot 32.48 \cdot mm)}{0.79^3 \cdot mm^3}\right]^{\frac{1}{4}} = 327.947mm$$

$$s_w := \sqrt{60^2 mm^2 + 153^2 \cdot mm^2} = 164.344mm$$

$$\text{if} \quad \frac{l_b}{s_w} = 1.995 < 2$$

$$b_d := 2 \cdot b_p + b_s = 122.22mm$$

$$k_{wo} := \sqrt{\frac{s_w + 2 \cdot b_d}{s_w + 0.5 \cdot b_d}} = 1.347$$

$$k_w := k_{wo} - (k_{wo} - 1) \cdot \left[\frac{2 \cdot l_b}{s_w} - \left(\frac{l_b}{s_w}\right)^2\right]$$

$$k_w = 1.343$$

For one central flange stiffener, the elastic critical buckling stress **σ**cr.s should be obtained from:

$$\sigma_{cr.s} := \frac{(4.2 \cdot k_w \cdot E)}{A_{s1} \cdot t} \cdot \sqrt{\frac{I_{s1} \cdot t^3 \cdot t}{4 \cdot b_p^2 \cdot (2 \cdot b_p + 3 \cdot b_s)}} = 176.603 \frac{N}{mm^2} \qquad (5.22)$$

Determination of the position of centroidal axis when the web and the stiffeners in the top flange are fully effective

For symbols see figure 5.14 of EN 1993-1-3:

l	z	l*z
30.358	0	0
16.24	3.02	49.0448
31.79	15.6	495.924
16	37.3	596.8
70.46	77.1	5432.466
16	116.89	1870.24
32.21	138.4	4457.864
20.8	153	3182.4
233.858		16084.74

$\Sigma l := 233.858\,mm$

$\Sigma lz := 16084.74\,mm^2$

$e_c := \frac{\Sigma lz}{\Sigma l} = 68.78\,mm$

$e_c = 0.069\,m$ -the bending moment capacity is governed by the compression stress at the top flange

WEB

Effective widths in the web (see clause 5.5.3.4.3)

For symbols see figure 5.14 of EN 1993-1-3

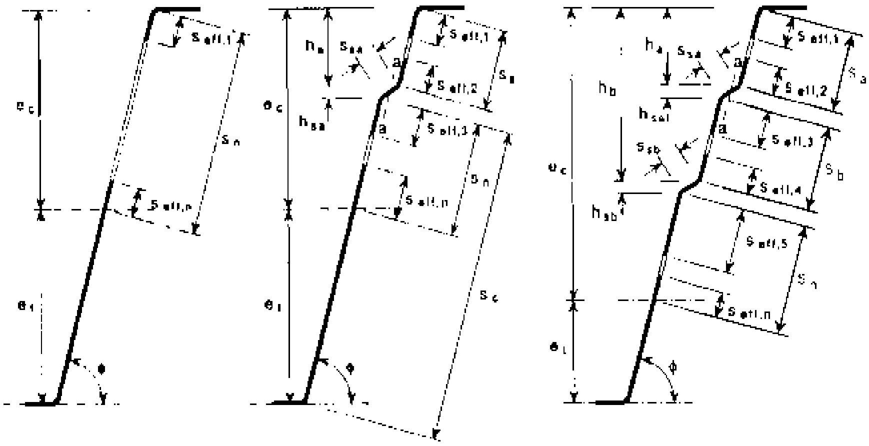
Initially the location of the centroidal axis houl be based on the effective cross-section of the flangebut the gross cross-sections of the webs. In this case the basic effective width Seff0 should be obtained from:

$\sigma_{com.Ed} := 256.72\frac{N}{mm^2}$ $\gamma_{M0} := 1$

$$S_{eff.0} := 0.76 \cdot t \cdot \sqrt{\frac{E}{\gamma_{M0} \cdot \sigma_{com.Ed}}} = 17.172\,mm \qquad (5.32)$$

$\sigma_{com.Ed}$ is the stress in the compression flange when the cross-section resistance is reached

$t := 0.79\,mm$



$$h_a := 31.2 \cdot mm$$

$$h_{sa} := 12.21 \cdot mm$$

$$S_{eff.1} := S_{eff.0} = 17.172\,mm \qquad (5.33a)$$

$$S_{eff.2} := \left(1 + 0.5 \cdot \frac{h_a}{e_c}\right) S_{eff.0} = 21.067\,mm \qquad (5.33b)$$

$$S_{eff.3} := S_{eff.0} \cdot \left[1 + 0.5 \cdot \frac{\left(h_a + h_{sa}\right)}{e_c}\right] = 22.591\,mm \qquad (5.33c)$$

$$S_{eff.n} := 1.5 \cdot S_{eff.0} = 25.758\,mm \qquad (5.33f)$$

If S.eff1+S.eff.2 > S.a the whole of S.a is effective, so revise as follows:

$$S_a := 32 \cdot mm$$

$$S_{eff.1} := \frac{S_a}{2 + 0.5 \cdot \frac{h_a}{e_c}} = 14.37\,mm \qquad (5.35a)$$

$$S_{eff.2} := S_a \cdot \frac{\left(1 + 0.5 \cdot \frac{h_a}{e_c}\right)}{2 + 0.5 \cdot \frac{h_a}{e_c}} = 17.63\,mm \qquad (5.35b)$$

If S.eff3+S.eff.n > S.n the whole of S.n is effective, so revise as follows:

$$S_n := 27.175mm$$

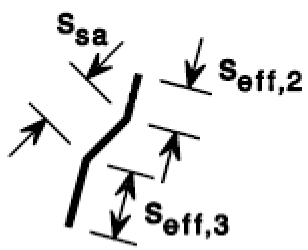
$$S_{eff.3} := S_n \cdot \frac{1 + 0.5 \cdot \frac{(h_a + h_{sa})}{e_c}}{2.5 + 0.5 \cdot \frac{(h_a + h_{sa})}{e_c}} = 12.697mm \qquad (5.36a)$$

$$S_{eff.n} := \frac{1.5 \cdot S_n}{2.5 + 0.5 \cdot \frac{(h_a + h_{sa})}{e_c}} = 14.478mm \qquad (5.36b)$$

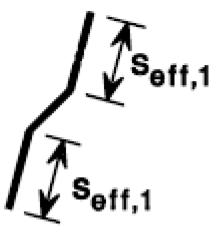
Web stiffener (see clause 5.5.3.4.3)

Cross section for determination of A.s (see figure 5.15)

Cross section for determination of I.s (see figure 5.15)



Cross-section for determining A_s



Cross-section for determining I_s

$$S_{sa} := 16 \cdot mm$$

$$A_{sa1} := S_{sa} + S_{eff.2} + S_{eff.3} = 46.327\,mm$$

$$I_{s1} := 16\cdot mm\cdot\frac{10.34^2\cdot mm^2}{12} + \left(2\cdot S_{eff.1}\right)\cdot\left(\frac{10.34\,mm}{2}\right)^2 = 910.76\,mm^3$$

For a single stiffener, the elastic critical buckling stress σ.cr.sa should be determined using;

$$S_c := 115\cdot mm$$

$$s_1 := 0.9\cdot\left(S_a + S_{sa} + S_c\right) = 146.7\,mm \qquad (5.39b)$$

$$s_2 := s_1 - S_a - 0.5\cdot S_{sa} = 106.7\,mm \qquad (5.39d)$$

$$k_f := 1$$

$$\sigma_{cr.sa} := \frac{1.05\cdot k_f\cdot E\cdot\sqrt{I_{s1}\cdot t\cdot t^3\cdot s_1}}{A_{sa1}\cdot t\cdot s_2\cdot\left(s_1 - s_2\right)} = 322.027\,\frac{N}{mm^2} \qquad (5.39a)$$

Interaction of flange and web stiffener should be taken into account according clause: 5.5.3.4.4

$$h_{ha} := 12.21\cdot mm$$

$$\beta_s := 1 - \frac{\left(h_a + 0.5\cdot h_{ha}\right)}{e_c} = 0.458 \qquad \text{for a profile in bending}$$

$$\sigma_{cr.mod} := \frac{\sigma_{cr.s}}{\sqrt[4]{1 + \left(\beta_s\cdot\frac{\sigma_{cr.s}}{\sigma_{cr.sa}}\right)^4}} = 176.428\,\frac{N}{mm^2} \qquad (5.42)$$

Reduced thickness ratio for flange and web stiffener according to clause 5.5.3.1.(7)

$$\lambda_d := \sqrt{\frac{f_{yb}}{\sigma_{cr.s}}} = 1.362 \qquad (5.12d)$$

$$\chi_d := 1.47 - 0.723\lambda_d = 0.485 \qquad (5.12b)$$

$$\frac{t_{red}}{t} := 0.485$$

Element	l	t.red/t	A/t	z	A*z/t	A*z*z/t	h	A*h*h/12t
1	16.24	0.485	7.8764	3.02	23.78673	71.83592	6.04	23.94530619
2	15.458	0.485	7.49713	0	0	0	0	0
3	15.458	1	15.458	0	0	0	0	0
4	14.37	1	14.37	6.88	98.8656	680.1953	13.8	228.0519
5	17.63	0.485	8.55055	22.26	190.3352	4236.863	17	205.9257458
6	16	0.485	7.76	37.3	289.448	10796.41	12.21	96.407718
7	12.697	0.485	6.158045	49.07	302.1753	14827.74	12.14	75.63085074
9	57.763	1	57.763	82.68	4775.845	394866.9	55.09	14608.78305
10	16	1	16	116.89	1870.24	218612.4	12.21	198.7788
11	32.21	1	32.21	138.4	4457.864	616968.4	30.415	2483.048031
12	20.08	1	20.08	153	3072.24	470052.7	153	39171.06
			193.7231		15080.8	1731113		57091.6314

$$e_c := \frac{15080.8\,mm^2}{193.72\,mm} = 77.848\,mm$$

$$\frac{I}{t} := 1731113\,mm^3 + 57091.63\,mm^3 - e_c^2 \cdot 193.72\,mm = 6.142 \times 10^5 \cdot mm^3$$

$$M_{crd} := 614201\,mm^3 \cdot \frac{0.79\cdot mm}{e_c} \cdot 327 \cdot \frac{N}{mm^2} \cdot \frac{2}{280 \cdot mm} = 1.456 \times 10^4\,N$$

$$M_{sheet} := M_{crd} \cdot 873 \cdot mm = 12.709\,kN \cdot m$$

5.2 Comparison of the results, sheet H150

H 150	Ultimate bending moment [kNm]	U. bending moment / Experimental test [%]
AISI 2007	13.27	93.31
EN 1993-1-3	12.7	89.31
Ansys APDL	14.01	98.52
Experimental test	14.22	

Table.2

5.3 Comparison of the results, sheet H55

H55	Ultimate bending moment [kNm]	U. bending moment / Experimental test [%]
AISI 2007	8.04	102.81
EN 1993-1-3	7.63	97.57
Ansys APDL	7.67	98.08
Experimental test	7.82	

Table.3

5.4 Comparison of the results, sheet H68

H68	Ultimate bending moment [kNm]	U. bending moment / Results from Ansys APDL [%]
AISI 2007	4.026	78.69
EN 1993-1-3	3.66	71.54
Ansys APDL	5.116	
Experimental test		

Table.4

5.5 Comparison of the results, sheet EUROCOL 60

EUROCOL 60	Ultimate bending moment [kNm]	U. bending moment / Experimental test [%]
AISI 2007	4.54	108.61
EN 1993-1-3	3.78	90.43
Ansys APDL	4.46	106.69
Experimental test	4.18	

Table. 5

For this project two procedures were tested for four type of sheets, one according to the North-American approaches and one that follows the European standards. The results show similarities with the experimental test results, except for sheet H68 which will be tested in the near future at Escola Tecnica Superior d'Enginyeria Industrial de Barcelona. The values that were obtained are under 10% of a difference from the experimental results which is a reasonable result and can be accepted for this type of research.

6. BUDGET

The budget is included under two headings: labor and material used.

- **Labor**

Staff	Worked days	Hours/day	Total hours	€/hour	Cost [€]
Project manager	80	1	80	100.00	8000.00
Student	80	6	480	10.00	4800.00
Subtotal					**12800 €**

- **Materials used**

Concept		Life expectancy [years]	Cost [€]	Amortized cost [€]
Hardware	Computer	5	1000.00	200.00
Software	Ansys	2	6000.00	3000.00
	Mathcad	1	460.00	460.00
	Autocad	1	2420.00	2420.00
	Microsoft Office	5	600.00	120.00
Expendables	Office materials	1	200.00	200.00
	Energy	1	100.00	100.00
Subtotal				**6500.00 €**

- **TOTAL**

Concept	Cost [€]
Labor	12800.00
Materials used	6500.00
Subtotal	19300.00
V.A.T. (21%)	4053.00
TOTAL	**23353.00 €**

7. ENVIRONMENTAL IMPACT

The main scope of the thesis is to elaborate a calculation method for trapezoidal steel sheets. With the Mathcad files already generated the project makes an easier working plane for users.

The generalized macros allows an efficient and time saving approach of the Finite Element Method with the minimum amount of time used to carry out the analysis.

The experimental test presents a perfect guide for all the types of thin-walled cold-formed trapezoidal steel sheets test that the clients or the manufacturer want to realise.

The environmental impact on the project is due to:

- Power and energy saving
- Efficiency and time saving
- Easier result interpretation

8. CONCLUSION

The scope of the thesis is to determine the ultimate bending moment for four type of sheets with different kind of methods. Even though the obtained results show similarities there are advantages and disadvantages that show themselves during the procedure.

The North-American approach is an easy way to determine the ultimate bending moment of the sheet. Using the Finite Strip method together with the CUFSM software makes an easy and time saving procedure that show results under 10% of difference from the experimental tests. It gives little room for the user to commit mistakes with the small numbers of variables used during the methods.

The European approach is a more complex method that uses a lot of variables and iterations till it arrives to the final results. It gives a lot of room to errors and is more difficult for the user to carry out an analysis.

From the software point of view Ansys APDL is the perfect program to this types of researches, the macros make the modelling fast for a variety of sheets, with different geometry and thickness. Furthermore helps the user to generate a multiple type of sheets with slight modifications in the macro. The software seems to be a good scientific tool for the research, but for the designing part its not necessary to use a software with such performance and complexity.

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