

# Simulation of the Roll-Forming Process for the Determination of the Relevant Residual Stresses of Cold-Formed Steel Members

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## Abstract

The uprights for pallet rack systems are usually thin-walled open cold-formed steel sections. Their behaviour under compression can be analysed experimentally, analytically or by finite element simulation. In the finite element simulation usually material non linearity, large displacements and initial geometric imperfections are introduced. But until now, the effect of the residual stresses due to the forming process, is usually non considered. With the aim of introducing these stresses in the finite element simulation, our group has started to simulate the roll-forming of open steel sections. In this paper we present our first experiences in the simulation of roll-forming of U-, C- and trapezoidal sections, some comparisons with experimental data available in the literature and the first results of the forming of a medium load upright section.

**Keywords:** Cold-formed steel, Finite element method, Residual strains, Residual stresses

## 1. Introduction

The structural behaviour of cold-formed thin-walled steel members has been one of the main research subjects of our group in the last years. Special attention has been focused on the stability under compression of uprights for pallet rack systems and their modes of buckling [1], [2].

The analyses have been carried out experimentally, analytically and by simulation with finite elements. In the finite element simulations material non linearity and large displacements have been included, and also the effect of initial geometric imperfections has been considered.

But the effect of the residual stresses that are generated in the roll- forming (the usual way to produce the uprights) has not been yet considered by us in our finite element simulations. So it was decided to introduce also this effect, and we started some months ago to do numerical simulations of the roll-forming process of thin-walled steel members, by using the COPRA RF and COPRA FEA software. The final aim of these simulations is to obtain the residual stresses in the section, and introduce them in the finite element analyses of the stability of uprights.

With this paper we present our first experiences in the use of the COPRA software, some comparisons with experimental results available in the literature, and the first results of residual strains and stresses obtained in the simulated roll-forming of a typical medium load upright section.

## 2. Simulation of roll-forming of an U-section

The first roll-forming process simulated has been the forming of an U-section (102,7 x 51,4 , t = 1,22 mm), made of carbon steel ( $f_y = 329$  MPa,  $E = 2,1 \cdot 10^5$  MPa,  $f_u = 420$  MPa,  $\epsilon_u = 0,22$ ). The process consists of 6 forming stands and 2 final rectification stands. The width of the sheet is 100 mm and the length is 450 mm, and the distance between stands is 350 and 400 mm.

Because of symmetry only half of the section has been modelled. Brick elements, type 7, with 8 nodes have been used. Two different meshes have been compared (see Fig. 1 and 2):

- MU1: 16 divisions x 2 layers x 61 lines = 1952 elements
- MU2 : 23 divisions x 2 layers x 61 lines = 2806 elements

For both meshes transverse and longitudinal residual strains (Fig.3 and 4) and longitudinal residual stresses (Fig. 5) have been determined. For model MU2 the longitudinal residual strains have also been separated into the bending component and the membrane component (Fig. 6). In all the figures coordinate  $s = 0$  corresponds to the node in the centre of the section (symmetry plane of the section), and the highest value of  $s$  to the extreme node (flange or lip, as the case may be). The results are similar in both cases, being values of MU2 higher in some nodes.

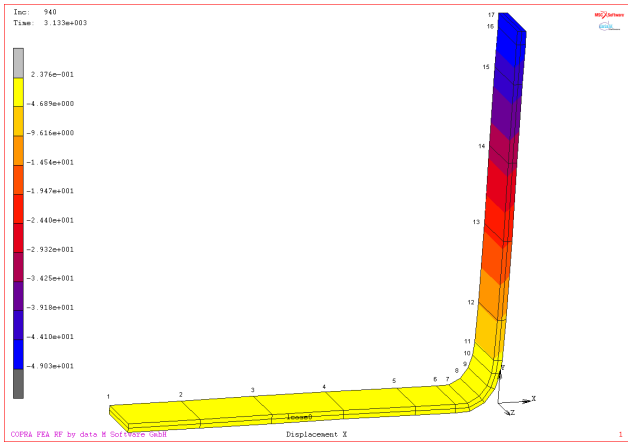


Fig. 1 Mesh of the model MU1

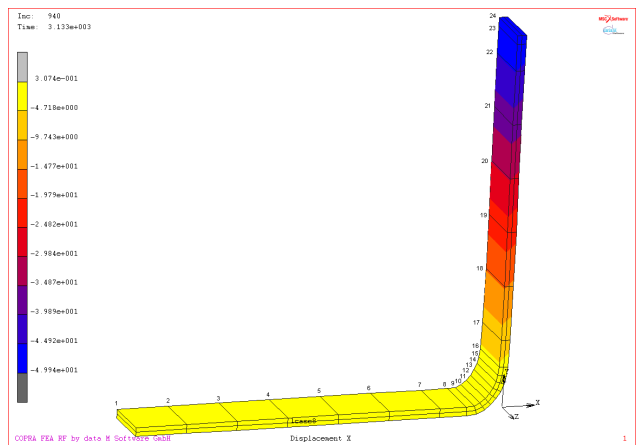


Fig. 2 Mesh of the model MU2

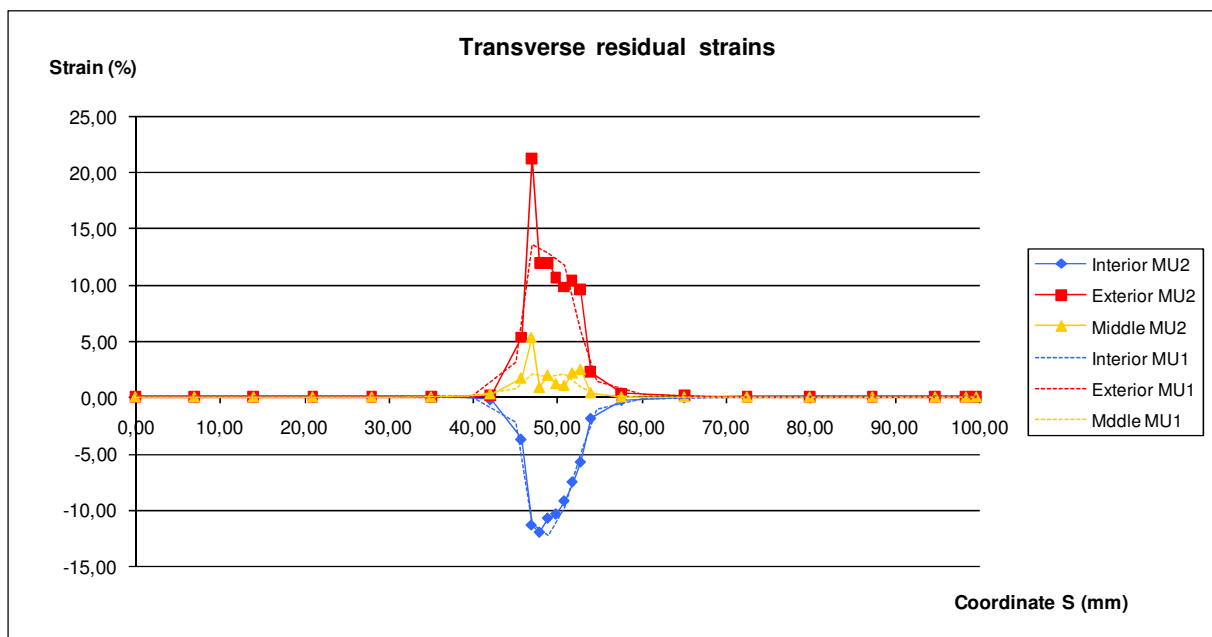


Fig. 3 Comparison of transverse residual strains, obtained with models MU1 and MU2

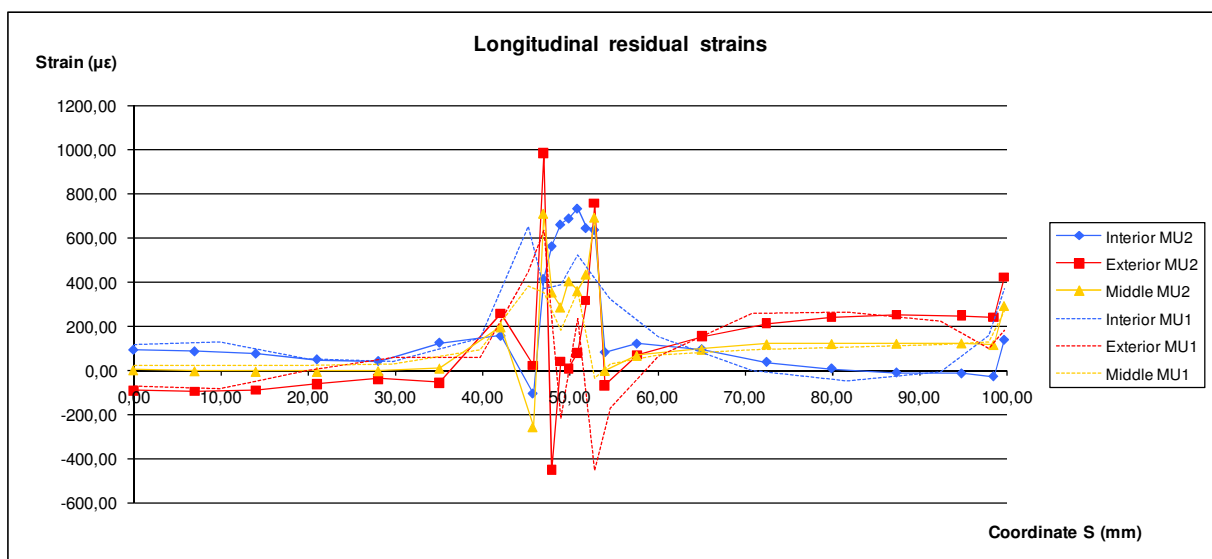


Fig. 4 Comparison of longitudinal residual strains, obtained with models MU1 and MU2

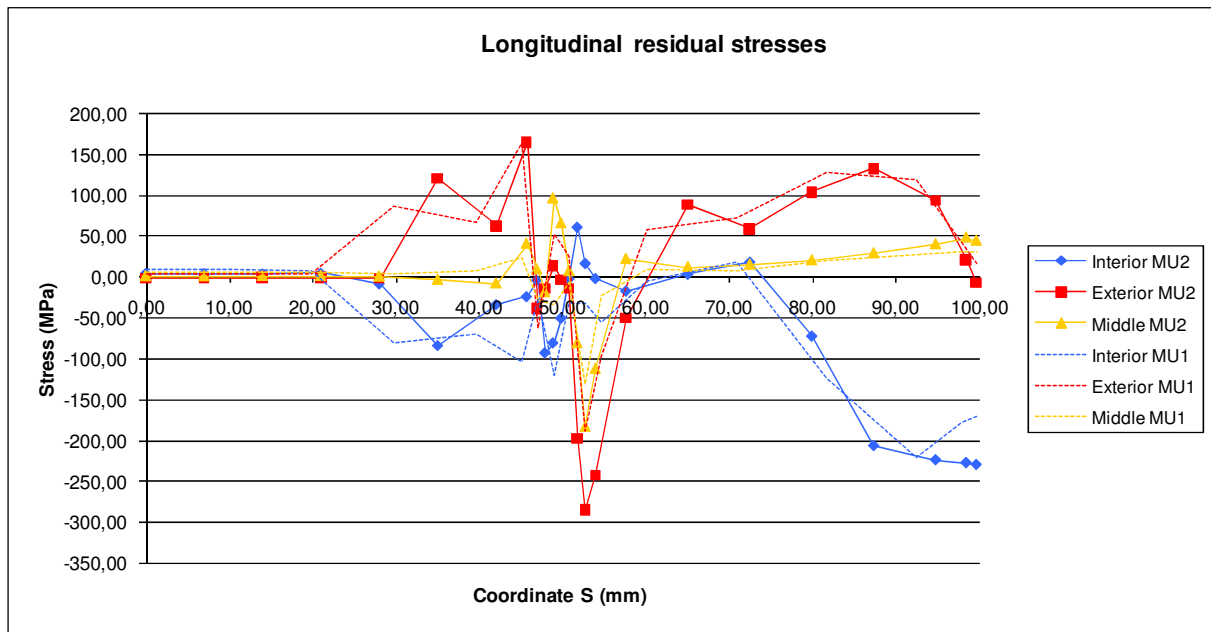


Fig. 5 Comparison of longitudinal residual stresses obtained with model MU1 and MU2

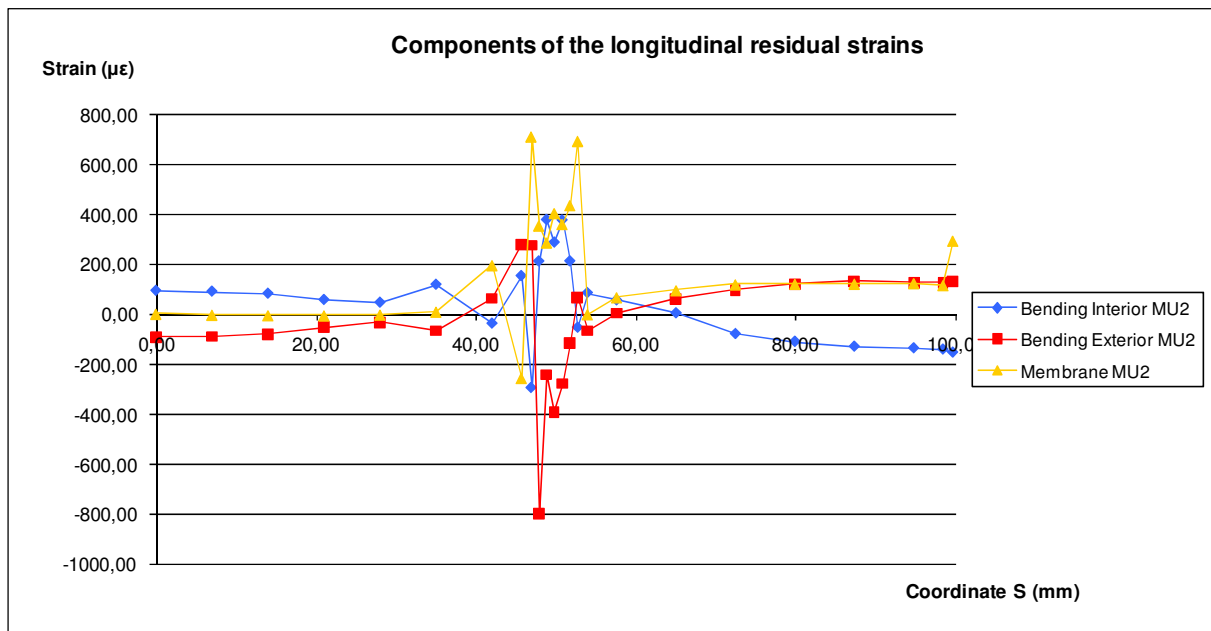


Fig. 6 Separated components of the longitudinal residual strains obtained with model MU2

### 3. Simulation of roll-forming of a C-section

Next the forming of a C-section (102,7 x 40 x 11,4 ,  $t = 1,22$  mm) has been simulated. The sheet has the same dimensions and material as the U-section analysed before. The process has 11 forming stands and 2 final rectification stands. The lip is first formed, and then the flange is bended.

Because of symmetry only half of the section has been modelled. Brick elements, type 7, with 8 nodes have been used. Two different meshes have been compared (see Fig. 7 and 8):

- MC1: 21 divisions x 2 layers x 61 lines = 2562 elements
- MC2: 29 divisions x 2 layers x 61 lines = 3538 elements

For both meshes transverse residual strains (Fig. 9) and longitudinal residual stresses (Fig. 10) have been determined. The results are similar in both cases, also in this case the finer mesh (MC2) gives higher values in some nodes.

Comparing the results of the U-section and the C-section:

- Transverse residual strains (Fig. 3 and Fig. 9): the values at the corner between web and flange are very similar in both sections; and in the C-section additionally appear the strains of the corner between flange and lip.
- Longitudinal residual stresses (Fig. 5 and Fig. 10): the values at the web and the flange follow the same pattern and are very similar; and in the C-section the lip introduces a different and specific distribution of stresses.

A first conclusion is that these results are coherent and that the simulation procedure is consistent: it reproduces the same values where the process is identical, and the values vary only where the process is changed.

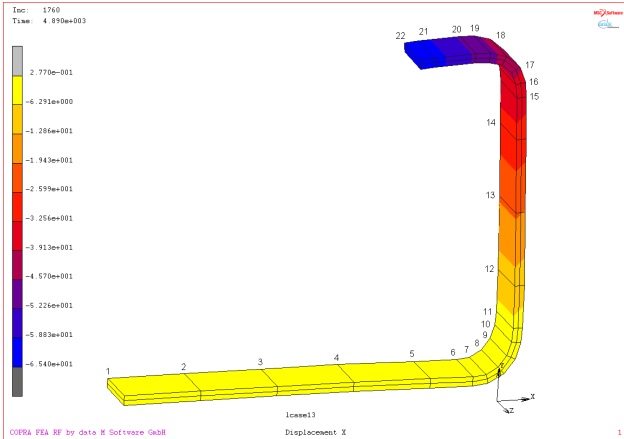


Fig. 7 Mesh of the model MC1

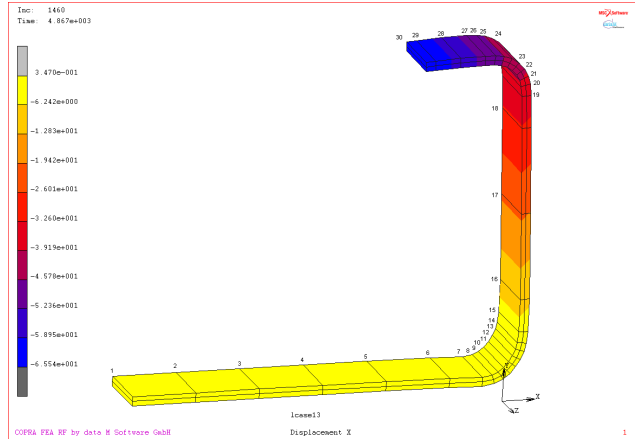


Fig. 8 Mesh of the model MC2

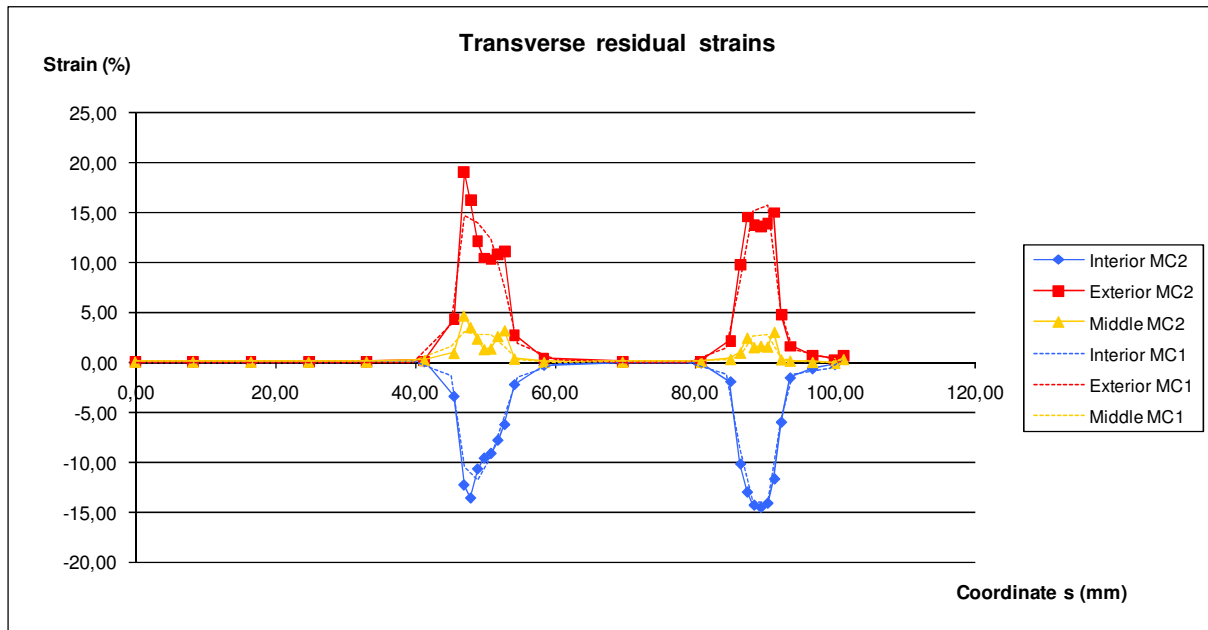


Fig. 9 Comparison of transverse residual strains, obtained with models MC1 and MC2

#### 4. Comparison with experimental data

The roll-forming of a trapezoidal channel section (web = 20 mm, flanges = 10 mm, flange angle = 80°, t = 0,6 mm) has been simulated (2 stands: 0° – 40° – 80°), and the results compared to the experimental ones given in [3]. Strains are measured at 1,5 mm of the flange's end. As can be seen in Fig. 11, the results agree well.

The roll-forming of an U-section (100 x 75, t = 4 mm) has also been simulated (3 stands: 0° - 30° – 60° – 90°), and the results compared to the experimental ones given in [4] and [5]. Strains are

measured at the internal face of the flange, at 2 mm from the extreme. As can be seen in Fig.12, also in this case the values agree well.

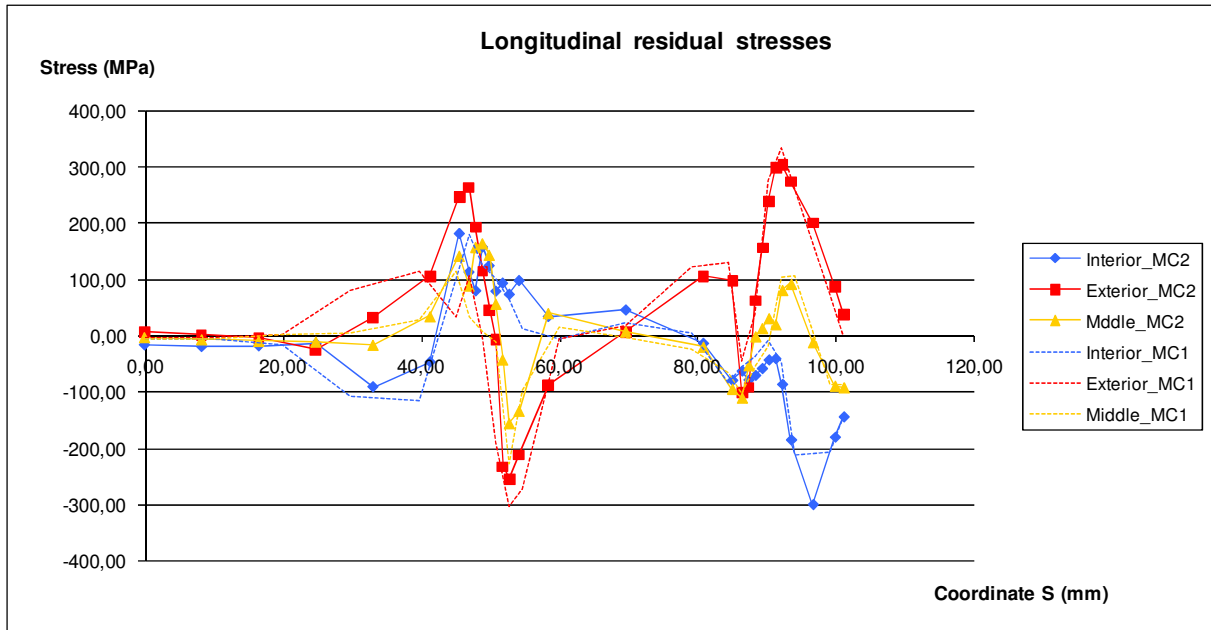


Fig. 10 Comparison of longitudinal residual stresses, obtained with models MC1 and MC2

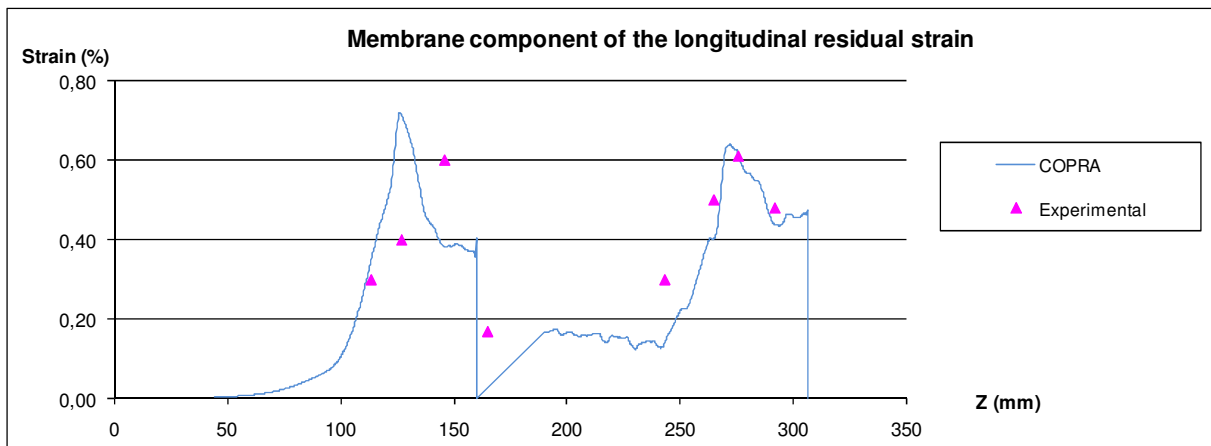


Fig. 11 Channel trapezoidal section: comparison with experimental results

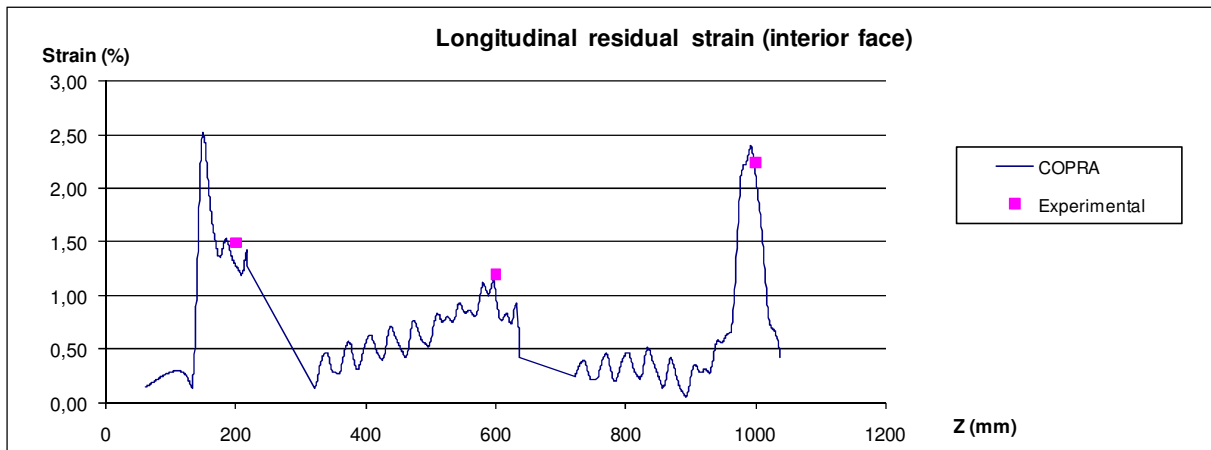


Fig. 12 U-section: comparison with experimental results

## 5. Simulation of roll-forming of an upright section

The roll-forming process of a typical medium load upright section for pallet rack systems has been simulated (see Figs. 13 and 14). The process has 20 forming stands and 1 rectification stand. The distance within stands is 350 and 400 mm. The steel sheet has a length of 450 mm and a width of 119,5 mm (corresponds to half of the section, because of symmetry), and is made of carbon steel ( $f_y = 502,5$  MPa,  $E = 2,1 \cdot 10^5$  MPA,  $f_u = 700$  MPa,  $\epsilon_u = 0,22$ ). The process has been adjusted until an acceptable result has been obtained: without wrinkling of the sheet or buckling (see Fig. 14). The final geometry of the formed section shows some geometric differences with the nominal section, and so the design of the rolls has still to be improved. Nevertheless, the results are useful to start an analysis of the residual stresses generated by the roll-forming process.

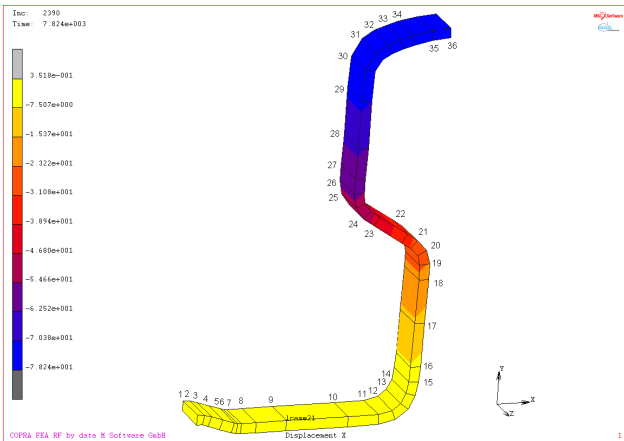


Fig. 13 Mesh of the model MP1

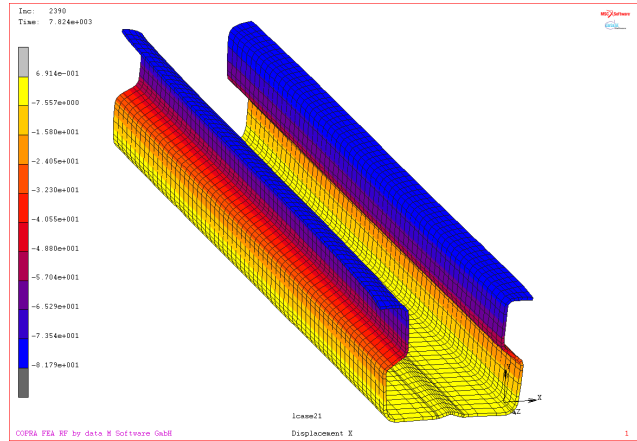


Fig. 14 Simulated roll-formed upright MP1

## 6. Analysis of residual strains and stresses

The value of the transverse and longitudinal residual strains along a central section of the conformed sheet is represented in Figs. 15 and 16. The 0 s coordinate corresponds to node 1 (centre of the section), and the 120 s coordinate to the node 36 (outer extreme of the lip). The peak values obtained are resumed in Table 1.

The value of the longitudinal residual stresses is represented in Fig. 17, and the peak values are summarised in Table 2.

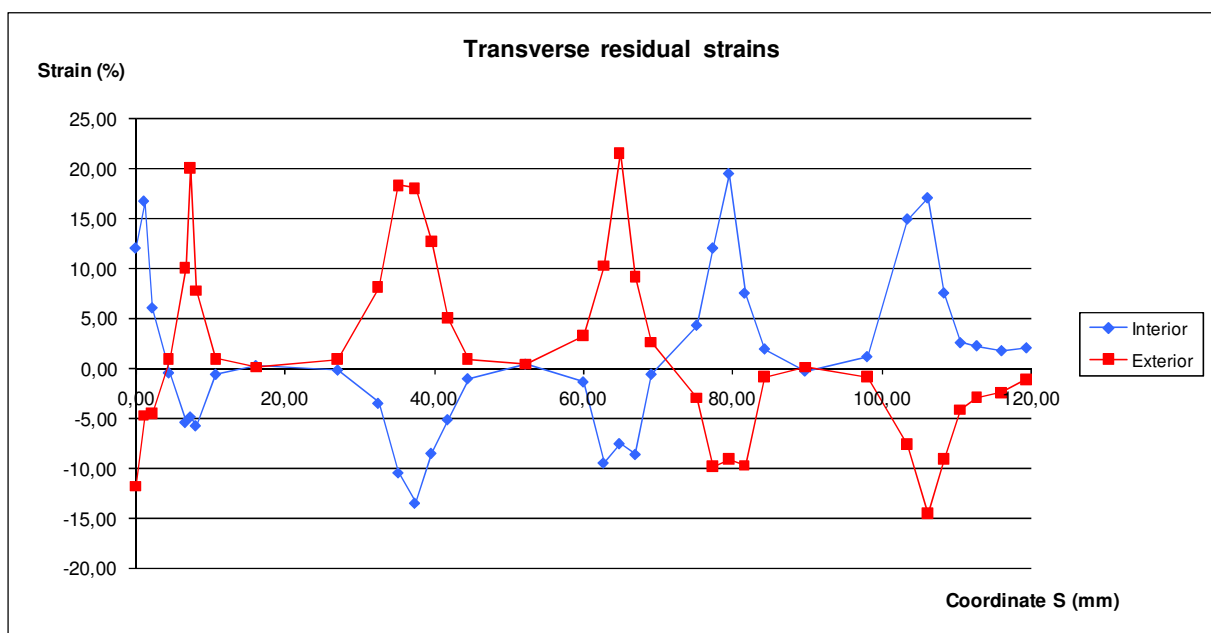


Fig. 15 Distribution of transverse residual strains obtained with model MP1

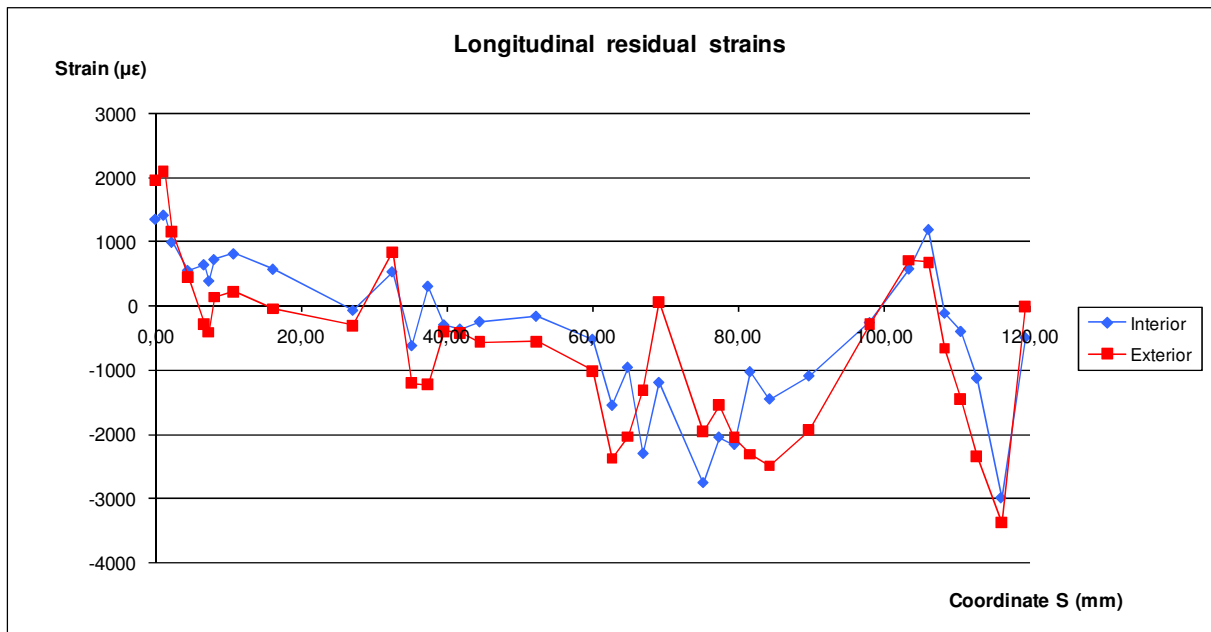


Fig. 16 Distribution of longitudinal residual strains obtained with model MP1

Node		1	5	13	20	25	31	35
Exterior	Transversal	-12	+20	+18	+22	-9	-15	-1
	Longitudinal	+0,20	-0,05	-0,11	-0,12	-0,22	-0,07	-0,34
Interior	Transversal	+12	-5	-14	-8	+20	+8	+2
	Longitudinal	+0,13	+0,05	+0,04	-0,22	-0,10	0	-0,30

Table. 1 Peak values of residual strains obtained with model MP1 (strains in %)

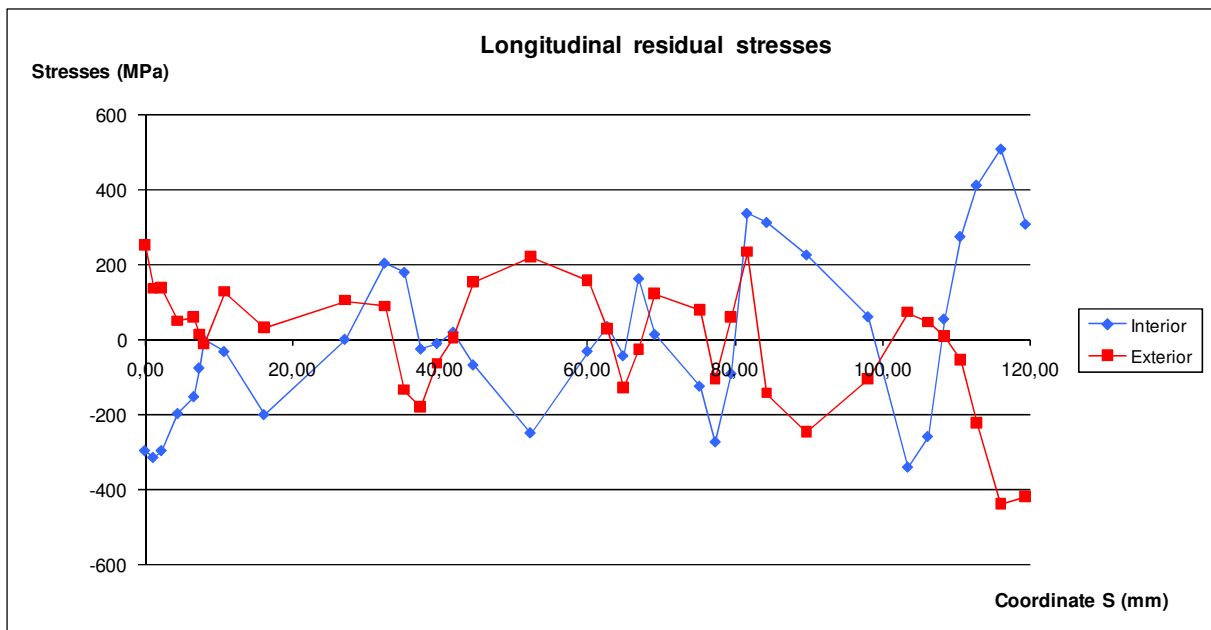


Fig. 17 Distribution of longitudinal residual stresses obtained with model MP1

Node	1	12	17	28	30	35
Exterior	+250	-150	+210	-220	+75	-420
Interior	-300	+180	-230	+210	-350	+500

**Table. 2** Peak values of residual stresses obtained with model MP1 (stresses in MPa)

## 7. Conclusions

With the use of the COPRA RF and COPRA FEA software it has been possible to simulate the roll-forming of the following sections:

- An U-section (102,7 x 51,4; t = 1,22 mm) and a C-section (102,7 x 40 x 11,4; t = 1,22 mm), obtaining consistent results, with different meshes.
- A channel trapezoidal section (20 x 10 (80°); t = 0,6 mm) and an U-section (100 x 75; t = 4mm), and to compare their results with experimental data available in the literature, with good agreement.
- An upright section (80 x 69; t = 1,8 mm), with a relatively complex shape, and to obtain the distribution of residual transverse and longitudinal strains and stresses.
- The values of the residual longitudinal stresses are high, and they probably will be significant when doing the stability analysis of the upright

The results obtained with the use of the COPRA software are very consistent and promising. The next steps in our research work will be:

- Refine the model and the process of the simulation of the upright section.
- Obtain the distribution of residual strains and stresses.
- Include these values as initial strains and stresses in our finite element models to do the stability analysis of the upright under compression.
- Also the possibility of doing some experimental measures of the residual strains in roll-formed uprights is being considered.

## 8. References

- [1] Casafont, M., Marimon, F., Pastor, M.M., “Calculation of pure distortional elastic buckling loads of members subjected to compression via the finite element method”, *Thin-Walled Structures*, 47, 2009.
- [2] Pastor, M.M., Casafont, M., Chillaron, E., Lusa, A., Roure, F., Somalo, M.R., “Optimization of cold-formed steel pallet racking cross-sections for flexural-torsional buckling with constraints on the geometry”, *Engineering Structures*, 2009.
- [3] Bhattacharyya, D., Smith, P.D., ”The Development of Longitudinal Strain in Cold Roll Forming and its Influence on Product Straightness”, *Advanced Technology of Plasticity*, 1984 vol. I.
- [4] Heislitz, F., Livatyali, H., Ahmetoglu, M.A., Kinzel, G.L., Altan, T., “Simulation of roll forming process with the 3-D FEM code PAM-STAMP”, *Jour. of Materials Processing Technology* 59 (1996).
- [5] Damm, K., “Ermittlung von Längsformänderungen beim Walzprofilieren und Standardprofilen auf einer mehrgerüstigen Anlage”, *Doctoral Dissertation*, TU Darmstadt.

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