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The beneficial influence of the roller-straightening process on the bearing capacity of steel columns

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Abstract

The roller-straightening process is a steel cold production technique which consists of passing a steel element through a series of rolls that bend the member, what leads progressively to a reduction of the initial geometrical imperfections along its weak axis. In addition, this post-treatment process induces a continuous yielding of the steel member and thus may present a second interest which is the reduction of the compression residual stresses at flange tips. This modification of the residual stress pattern could lead to an increase of the carrying capacity of steel columns.

Indeed, the capacity of columns in compression is evaluated through the European buckling curves reported in EN1993-1-1 in which the compression resistances are highly affected by the initial bow imperfections and residual stresses resulting from the rolling process.

However, whilst all long products seem to be systematically straightened nowadays, EN1993-1-1 does not consider the potential beneficial effect of the roller-straightening process. In other words, it means that the current recommendations of EN1993-1-1 neglect the potential benefit of this process on the buckling capacity.

In this context, a collaboration for a research study has been initiated between ArcelorMittal and the University of Liège to numerically estimate the residual stress patterns after the roller-straightening process of three relevant heavy H-shape profiles (HE 600 B, HE 500 M and HD 400 x 262) in HISTAR®460 and evaluate whether these new distributions could lead to a significant increase of the column bearing capacity.

Keywords

Roller-straightening, Flexural buckling, Residual stresses, Stability

1 Introduction

With the aim to respect the tolerances in terms of maximum bow imperfection, steel producers often use cold straightening to straighten profiles further to the rolling. To straighten structural shapes, either rolls or gag presses may be applied. According to Alpsten and Tall [1], both methods were already used inside the mill productions in 1970.

Amongst them, the roller-straightening process (also called “rotorizing” or “rotary straightening”) is a post-treatment in which the profile is passing through a train of rolls that bend the member, what leads progressively to a reduction of the amplitude of the initial geometrical imperfection. This process thus allows to straighten members along weak axis but also to subsequently reduce the residual stresses at flange tips. By contrast, in gag straightening, which is not covered in this paper, concentrated forces are applied locally along the length of the member to bend it to approximate straightness. Therefore, the residual stress redistributions are only observed at or near points of loading [2].

Nowadays, the roller-straightening is often applied to the whole production even for heavy hot-rolled sections. This feature has been confirmed in a publication of Ge & Yura in 2019 [3].

As partially described, this post-rolling process is likely to positively modify the values of three key parameters significantly influencing column buckling:

- the maximum bow imperfection as the process name indicates;
- the pattern of residual stresses: a decrease of the compression residual stresses at flange tips has been already reported in previous research as explained in Section 2;
- the apparent yield strength, which does not appear to be significantly affected according to the limited literature on the subject

In the scope of this pre-study, the initial out-of-straightness of L/1000 considered in Eurocode 3 [4] is kept and thus only the impact of "straightened residual stress patterns" on column buckling capacity is analysed. A suggestion was already made in an ECCS publication in 1976 to recognize the beneficial effects of roller-straightening in Eurocodes [5]. However, current European buckling curves prescribed in EN1993-1-1 [4] still do not consider this effect nowadays.

A recent study from Ge & Yura published in 2019 [3] addresses the rotary-straightening of columns by experimentally evaluating the residual stress patterns of a straightened W12x65 section and then, by assessing the influence of this experimental pattern on weak and strong axes column stability. This study expressed that, in the case where residual stresses are neglectable, it could provide up to 45% increase in strength for this section. The margin between the classical residual stress pattern and the no residual stress pattern is significant, thus considering a reduction of the residual stress amplitude may present a notable strength benefit. Herein, numerical investigations are performed on three selected European structural sections in HISTAR®460 [6] namely: HD 400 x 262, HE 500 M and HE 600 B. HISTAR® is a structural fine grain steel grade complying with the requirements of the European standards EN 10025-4:2019 for weldable fine grain steel and combining high strength, good toughness as well as superior weldability.

In this paper, a procedure to predict the evolution of the pattern of residual stresses with the variation of the setting parameters of the straightening process will be proposed and validated. Then, the influence of modified patterns on the carrying capacity of steel members in compression will be assessed and final conclusions will be drawn. A complete report has been written by the author containing all development details [6].

2 Background on residual stress patterns for straightened members

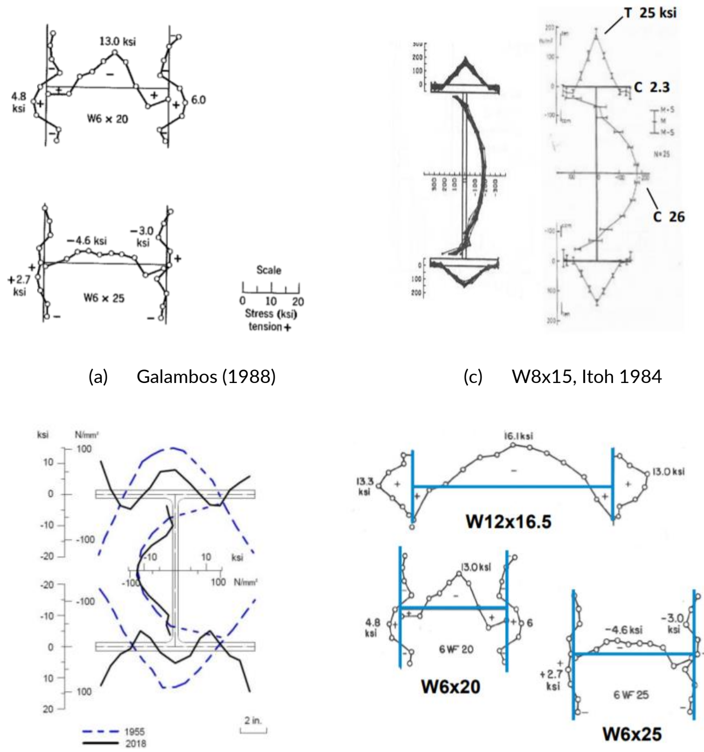
The concern for the effect of cold straightening on column bearing capacity has already been the subject of publications since the early 1970s. Indeed, the strength increase associated to the residual stress redistribution after this post-treatment process has already been contemplated by Frey in 1969 [7] and Alpsten in 1970 [8].

However, investigations had already started before. Indeed, Galambos reported residual stress diagrams for both straightening processes in his guide to stability design [2]. Amongst them, one from Huber [9] who already gave in 1956 a residual stress pattern of a W8x31 section after gag straightening about its weak axis. Residual stress distributions depending on the straightening procedure are also provided by Beedle & Tall in 1960 [10].

Pavlović & Stevens [11] have observed a strength loss which was attributed to the Bauschinger effect. Moreover, according to Tall in 1964 [12], the effect of steel grade on the residual stress patterns is not as significant as the geometry. These effects have been neglected in the scope of this study.

In addition, concerning the potential gain resulting from the roller-straightening process, Alpsten in some papers [13], [14] affirmed that the column bearing capacity may increase by 20% by conserving the same slenderness and the same out-of-straightness.

Given that only the roller-straightening process is investigated herein, only existing residual stress distributions for this process are reported in Figure 1.



(a) Galambos (1988)

(c) W8x15, Itoh 1984

(b) Ge & Yura, 2019

(d) Yura, Lu 1968

Figure 1: Residual stress distributions in the literature [2], [3].

For all these experimental data, few information is given concerning the way on how the straightening has been achieved; so, there are some fundamental unknowns such as the amplitude of the imposed displacements, for instance. Moreover, most of these experimental tests concerns American steel grades and sections and no systematic effect which would result from the straightening may be clearly identified. Therefore, the current knowledge about this research topic appears as too much limited to physically interpret these experimental results with the aim to define adequate straightened patterns for the profiles to be considered in the present study.

3 Validation of the numerical model

The FINELG software [15] is used all along this study in order to simulate the effect of roller-straightening on residual stress distributions but also to draw buckling curves. To again confirm the reliability of this software, the European buckling curves for the three selected profiles are drawn and compared with those from the current [4] and new forthcoming versions [16] of EN1993-1-1 (prEN1993-1-1). It is worth pointing out that the steel stress-strain relationship is elastic perfectly plastic, and strain-hardening is not modelled.

In addition, an out-of-straightness of L/1000 (where L represents the length of the steel profile) is considered as it is the case in EC3 European buckling curves. Similarly, these simulated curves are established by using classical residual stress distributions which result from hot-rolling procedure as recommended by Eurocode 3. The relevant European buckling curves for the selected profiles (according to EN1993-1-1 and prEN1993-1-1) as well as the results obtained by numerical simulations are reported in Figure 2. For the sake of readability and to avoid data overlapping, results are provided in their dimensional form.

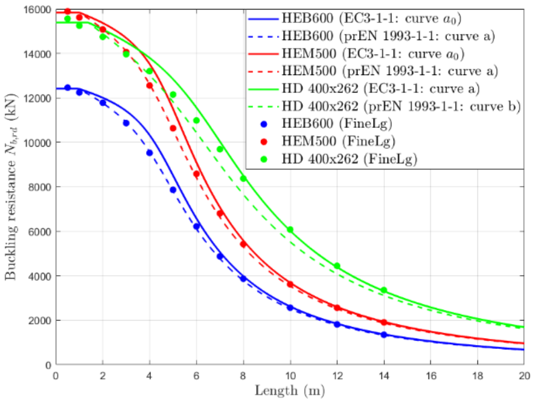


Figure 2: Buckling curves for the three selected sections.

According to Figure 2, it can be concluded that the FINELG software simulates well the European buckling curves and, therefore, this software can be adopted to investigate the effect of the residual stress redistribution on the buckling resistance and to define possible new reference buckling curves for straightened column members.

4 Numerical simulations of residual stress patterns

4.1 Approaches proposed in the literature

Frey has published a paper [7] in 1969 in which he derives analytically the shape and the maximum values of the residual stresses further to a straightening process. In this study, Frey considers that pure bending moment is progressively applied to the member until a stage at which, after releasing the applied moment, the profile is perfectly straight. The length L of the member to be straightened is fixed equal to 10 m and the initial out-of-straightness is also fixed equal to L/100. These values are obsolete compared to current values. Moreover, this mathematical model does not introduce any imposed displacements, the own goal is just to provide a straight member at the end of the process, what is not in line with the straightening process. These differences explain why inconsistent results were found in this research when comparing the Frey model with some other numerical results.

On the other hand, a paper [17] has been published by Guan in 2017 in which he studies the stress-inheriting behaviour of a H-beam during the roller-straightening process with repeated elastic–plastic bending and its effect on the section's bending properties. In addition, in this paper, the author has developed a MATLAB routine which numerically simulates the process of continuous bending of a H-beam and studies the law of sectional stress inheritance and its effect on the evolution of geometric imperfections. This numerical model is based on several assumptions expressed in the paper.

The idea pursued in this paper is to build a simplified numerical model in order to evaluate the potential benefit of the roller-straightening process on the residual stress amplitudes at flange tips. This simplified model consists in idealizing the roller-straightening process as a series of pure bending of curved beam as described in the following subsection. This assumption was also realised by Yin in 2014 [18].

4.2 Proposed model description

The roller-straightening process can be idealised as a continuous beam on five pinned supports subjected to four imposed displacements at each mid-span. The values 9 mm, 6 mm, 3 mm and 0,75 mm have been selected as reference. The reference parameter settings and displacements along the length of the continuous beam are shown in Figure 3.

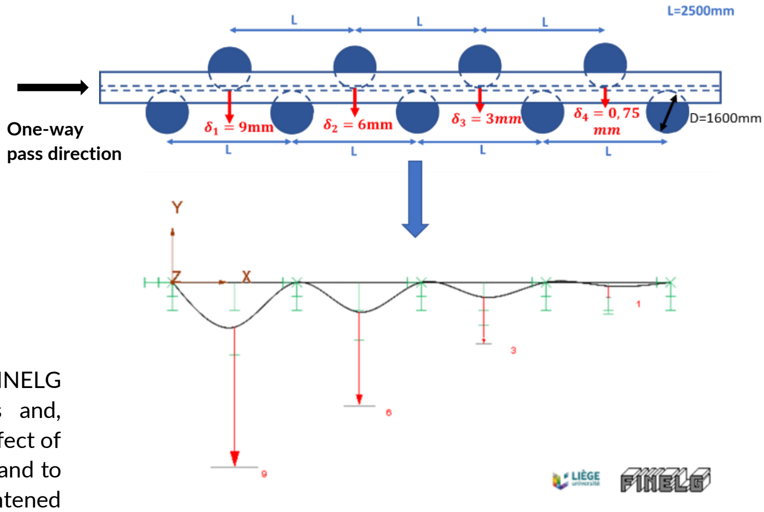


Figure 3: Idealisation of the roller-straightening process as a continuous beam.

This structure is statically indeterminate and represents the stage in which the member is fully inside the machine. However, the decision was taken to idealise this continuous beam by a series of statically determinate beams.

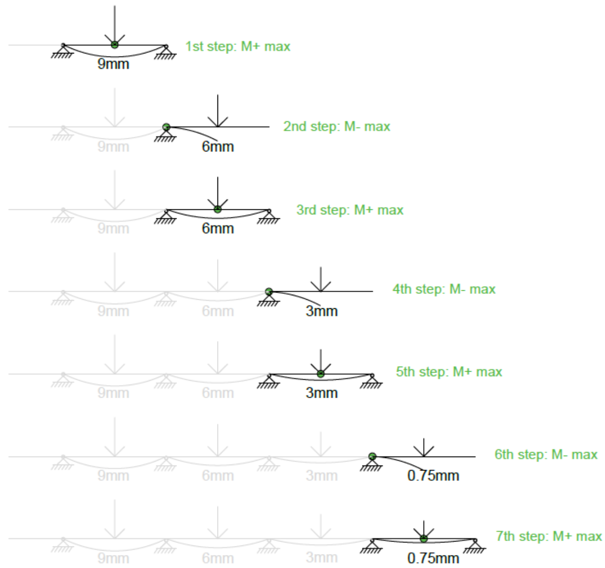


Figure 4: Decomposition of the roller-straightening process into simply supported beams.

As represented in Figure 4, the section marked with a green bullet point is alternatively subjected to positive and negative bending moments. Therefore, statically determinate systems are subjected to various imposed displacements at mid-span. In order to simulate the positive and negative bending moments, reference-imposed displacements are listed as follows (positive displacement axis is oriented vertically upward): $\delta_1 = -9\ mm,\ \ \delta_2 = +3\ mm,\ \ \delta_3 = -6\ mm,\ \ \delta_4 = +3\ mm,\ \ \delta_5 = -3\ mm,\ \ \delta_6 = +2.25\ mm,\ \ \delta_7 = -0.75\ mm$ and then a stress relaxation is allowed.

Although this methodology is quite easy to implement in a software, the idealisation of the continuous beam into several simply supported beams must be kept in mind.

4.3 Methodology example

The following investigations focus on the HD 400 x 262 section. The various displacements/steps are successively applied to the member according to the procedure using the values of reference-imposed displacements described in Figure 3. Using the MATLAB software [19] to extract all results from FINELG, the P-δ (load-displacement) relationship can be established. The P-δ curve is represented in Figure 5 below.

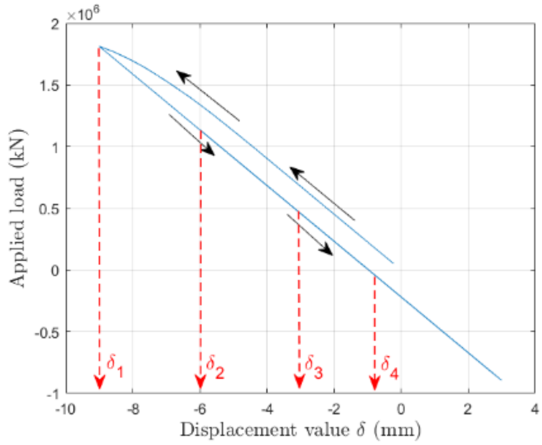


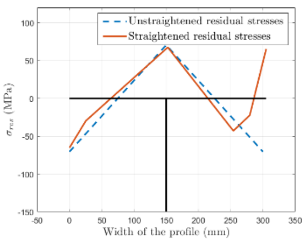
Figure 5: P-δ relationship during the roller-straightening process of the HD 400 x 262 profile.

As can be seen in Figure 5, only the first imposed displacement of 9 mm induces a yielding of the steel section reflected by the non-linearity in the curve. After this first loading, the section remains in the elastic field. The penultimate step in the methodology consists in determining the residual displacement after stress relaxation (for an applied load back to 0). This can be directly read in Figure 5, then this residual displacement is applied as the last step of the imposed displacement series into FINELG to reflect member bending stress relaxation.

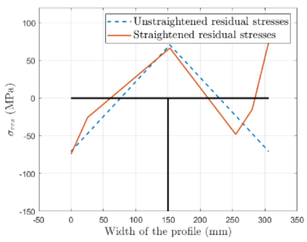
The final step in the methodology consists in extracting residual stresses after bending stress relaxation. Once it is done, the residual stresses before and after the roller-straightening process can be plotted in order to compare them and evaluate the influence of the roller-straightening process on the residual stress distributions. The bending around weak axis mostly affects stresses in flanges, so results will be only drawn in the flanges throughout this report.

4.4 Residual stress patterns for each selected profile

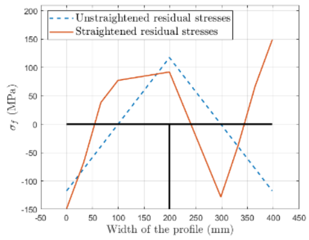
For the three profiles, yielding only occurs one time for the first positive bending which is induced by the first imposed displacement of 9 mm. After this first yielding, steel sections remain in the elastic field. The residual stress patterns in the flanges for the three steel profiles are reported in Figure 6.



(a) HE 600 B



(b) HE 500 M



(c) HD 400 x 262

Figure 6: Residual stress patterns after one yielding for the 3 studied profiles.

Figure 6 illustrates the fact that the magnitude of compression residual stresses is greatly reduced at the right flange tip for each of the three studied profiles. Indeed, the right-hand edge of each flange undergoes a change in the sign of the residual stresses which should lead to an increase in the buckling resistance. Conversely, compression residual stresses at the left flange tip of each flange are roughly the same for the two first profiles and bigger for the HD 400 x 262. This side will probably not lead to a better buckling resistance. Consequently, the positive impact of the roller-straightening process on the buckling resistance should depend on the direction in which the profile will buckle. This feature is addressed in Section 5.5.

4.5 Comparison with the Frey method

As previously explained, the Frey method is based on the yielding of the profile in such a way that, after releasing the applied bending moment, the steel profile is perfectly straight. A comparison between the FINELG method (1 yielding) and the Frey method for the HD 400 x 262 is provided in Figure 7.

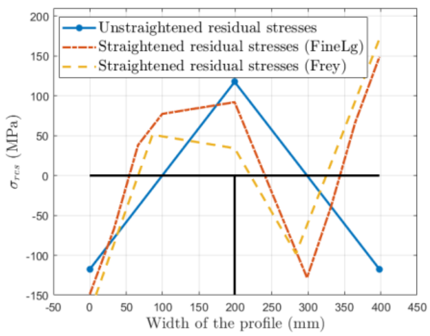


Figure 7: Comparison between the Frey method and the FINELG method.

Figure 7 illustrates the fact that the shape of the residual stress distributions is roughly the same between the two methods. It seems logical to get non equal magnitudes of residual stresses due to the different assumptions on which the two models are based. For instance, the Frey model is not related at all to imposed displacement values. Thus, the Frey model pattern shall always be the same whatever the imposed displacement values. However, this comparison enables to validate the developed numerical model.

5 Sensibility studies to establish relevant residual stress patterns

5.1 Effect of the amplitude of the first yielding

This subsection consists in trying to understand the influence of the first yielding amplitude on residual stress distributions, again in a one-way pass. Table 1 shows the various imposed displacement cases chosen so as to increase the yielding intensity (increase of δ_1 without any modification of the other displacements, so as to still ensure that no further plasticity is associated to δ_2, δ_3 and δ_4).

Table 1: Imposed displacement cases chosen to evaluate the effect of the first yielding amplitude.

Imposed displacements	$\delta_1[mm]$	$\delta_2[mm]$	$\delta_3[mm]$	$\delta_4[mm]$
Case 1	8	6	3	0.75
Case 2	9	6	3	0.75
Case 3	10	7	4	1.75
Case 4	11	8	5	2.75

The residual stress patterns for the four various cases are represented in Figure 8.

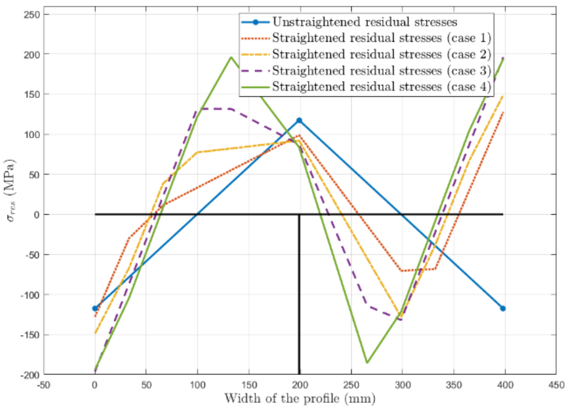


Figure 8: Residual stress patterns for the different imposed displacement cases and the HD 400 x 262 steel section.

Figure 8 shows that the higher the first imposed displacement, the higher the residual stresses at flange tips. Accordingly, it increases tension residual stresses on one side and compression residual stresses on the other side; so, the roller-straightening benefit will depend on the direction of the initial imperfection. In addition, the lower the first imposed displacement, the lower the amplitude of residual stresses on flanges. However, the amplitude of the first yielding must be sufficient to enable a second yielding of the cross-section. Indeed, the first yielding does not occur at the same time for the three studied profiles. Consequently, a first imposed displacement of 9 mm appears as suitable to enable a second yielding of the HD 400 x 262 cross-section while this value is not sufficient for the two other steel profiles, HE 600 B and HE 500 M. Therefore, the first imposed displacement must be well targeted in such a way to maximise the benefit of the roller-straightening on the column buckling capacity.

5.2 Effect of several successive yielding

The influence of several successive yielding on residual stress distributions has also been analysed. Various imposed displacement cases have been chosen as indicated in Table 2 so as to understand the effect of a second yielding. In fact, the second imposed displacement is increased with the aim to generate a second yielding under the first negative bending moment.

Table 2: Imposed displacements cases to evaluate the effect of several yielding.

Imposed displacements	$\delta_1[mm]$	$\delta_2[mm]$	$\delta_3[mm]$	$\delta_4[mm]$
Case 1	9	6	3	0.75
Case 2	9	5	3	0.75
Case 3	9	4	3	0.75
Case 4	9	3	3	0.75

The P-δ curves for cases 2, 3 and 4 are reported in Figure 9.

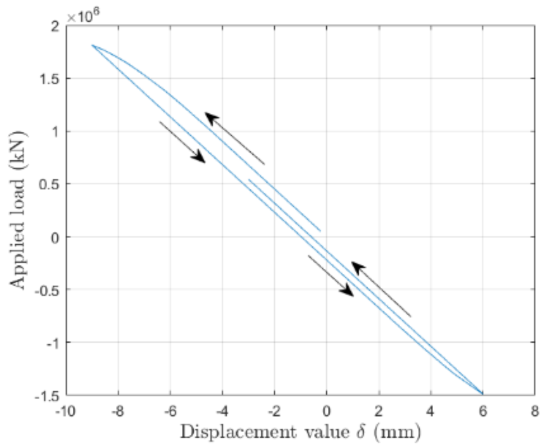


Figure 9: P-δ relationships for various imposed displacement configurations applied on the HD 400 x 262.

As can be seen in Figure 9, the first yielding amplitude must be sufficient to enable a second yielding of the steel cross-section as discussed in the previous section. Accordingly, there is a dependency between the straightening settings which depend on the desired degree of optimisation. The different residual stress patterns after the roller-straightening process in the four cases are given in Figure 10.

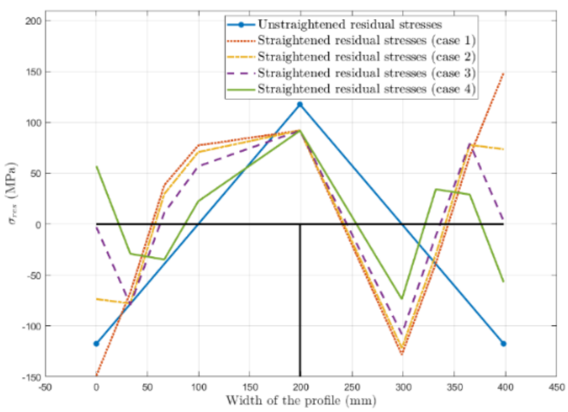


Figure 10: Residual stress patterns for the various imposed displacement cases and the HD 400 x 262 steel section.

As can be seen in Figure 10, the second cross-section yielding induces a bend in the residual stress distributions at flange tips. The smaller the second imposed displacement, the lower the compression residual stresses. This could be beneficial in view of an expected increase of the buckling resistance of columns.

Accordingly, it seems that optimised selections of the two first imposed displacements could be found in such a way to reduce the amplitude of the residual stresses.

5.3 Effect of a return straightening pass

The return pass does not induce a second yielding of the steel section. Consequently, the P-δ curve is the same as the one represented in Figure 5 and the return pass has thus no effect on the straightened residual stress pattern.

5.4 Effect of 2 one-way passes in various directions

In order to ensure that the profile is straight after the process, two successive passes through the machine in two directions (rotation along the axis by 180°) could be potentially contemplated. Although ArcelorMittal is not applying it, it has been decided here to simulate it numerically by the FINELG method so as to see its effect on the residual stress distributions.

The second one-way passes in the other weak axis side induces a second yielding of the section in such a way that the remaining displacement at the end is not affected by the first yielding. Consequently, the residual stress pattern is, thus, the inverse of the one with only one yielding of the cross-section.

The residual stress values for two one-way passes are the mirror values of the ones for the one-way pass. The effect of these patterns on buckling capacity will depend on the direction of the initial geometrical imperfection as discussed in the following subsection. Indeed, the tension residual stresses are located at different flange tips depending on the followed process.

5.5 Effect of direction (sign) of the geometrical member imperfection

The flexural buckling around weak axis presents two opposite stress patterns depending on the sign of the initial deformed shape. The application of an axial force on a geometrically imperfect column generates bending moments to which corresponds a bi-triangular stress pattern. Compression stresses develop at the intrados, in the left or right column side according to the sign of the initial imperfection. These compressive stresses are added to those associated to the compression force and to the residual stresses and it is known that column buckling appears when the maximum resulting compressive stress reaches f_y. By the way, this explains why higher residual stresses affect negatively column buckling.

For a usual residual stress pattern as the one reported in Figure 6c, the orientation (sign) of the geometrical imperfection is not influencing the column buckling resistance as the residual stress pattern is symmetrical with respect to the column web. But it is not the case for a "straightened one" as can also be seen in Figure 6c.

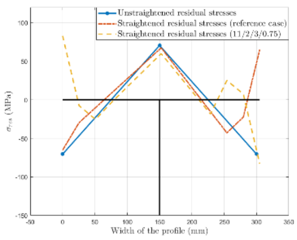
When the sign of residual stresses at flange tips are opposite in the two patterns, the residual stresses resulting from the roller-straightening process offset the unstraightened ones. Consequently, two possible combinations of the imperfection sign and the unsymmetrical residual stress pattern should be considered.

5.6 Summary of the observations and selection of relevant residual stress patterns

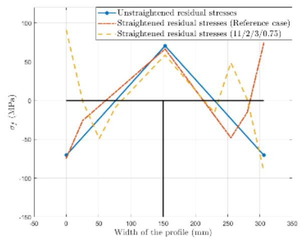
Several conclusions can be drawn from these numerical simulations and afterthoughts.

- Increasing too much the first imposed displacement d_1 leads to an increase of the compression residual stresses at the left flange tip and to an increase of the tensile residual stresses at the right flange tip. In addition, a global increase of the maximum values of the residual stresses is observed.
- Decreasing the second imposed displacement d_2 leads to a reduction of the residual stresses at flange tips, on both sides.
- A return straightening pass does not present interest, so it is not necessary to consider it further;
- The two one-way passes successively for two weak axis sides do not present any interest either.
- The orientation of initial geometrical imperfection could potentially influence the carrying capacity of straightened columns in which non-symmetrical residual stress patterns have been generated; this will be also raised later in the section on column buckling.

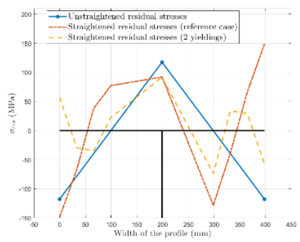
In view of studying the influence of roller straightening on the carrying capacity of columns in compression, residual stress patterns must be selected for each of the three profiles. The first residual stress pattern which will be considered is the one obtained by considering the reference-imposed displacements, i.e., 9/6/3/0,75 mm. As a second residual stress pattern, an "optimised" one will be considered to evaluate the benefit on buckling resistance which could be reached in the case of an optimised straightening process. It is important to mention that this optimisation is just based on the knowledge acquired from the previous sections; so better situations might have been found through a more accurate optimisation. However, the straightening should be seen in the future as a way to increase the competitiveness of steel profiles, further studies should be conducted first to optimise the straightening process and secondly to validate it through experimentations. Figure 11 illustrates the residual stress patterns chosen for each of the three steel profiles.



(a) HE 600 B



(b) HE 500 M



(c) HD 400 x 262

Figure 11: Residual stress patterns chosen for each of the three steel profiles.

As shown in Figure 11, each second residual stress pattern is characterised by a very low amplitude of compression residual stresses by comparison with the unstraightened and the reference residual stress patterns (obtained through a one-way pass with the reference setting of the machine). Consequently, higher increases of the buckling capacity are expected with this second residual stress pattern for each steel profile.

6 Influence of roller-straightening on column buckling resistance

The final part of the present pre-study consists in deriving buckling curves for straightened compression members, successively for the two here-above defined cases: reference and optimised straightening processes. In a second phase, they will be compared with those recommended in EC3 [1] so as to quantify the effect of the roller-straightening process on column bearing capacities. The buckling curves have been established by evaluating, for each of the three selected profiles, column instability loads for 13 different buckling reduced slendernesses corresponding to profile lengths of 0.1, 0.5, 1, 2, 3, 4, 5, 6, 8, 10, 12 and 14 metres. The steel stress-strain relationship, the shape and amplitude of the initial geometrical imperfection are the same as the ones considered in Section 3. As a reminder, only S460 steel grade complying with EN 10025-4:2019 is studied within the framework of this study, the benefit is likely to be higher for lower steel grades given their lower buckling resistances.

The implementation of non-standard patterns of residual stresses in FINELG is not automatic and therefore successive adjustments (balancing) are potentially required so as to be as close as possible to the "actual" sired pattern. Figure 12 illustrates the residual stresses for the reference case of the HD 400 x 262 section before and after balancing into the software.

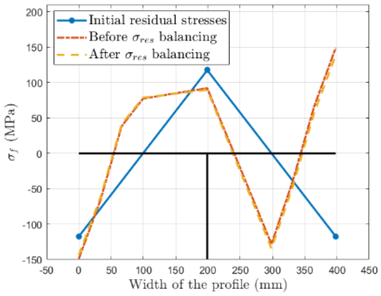
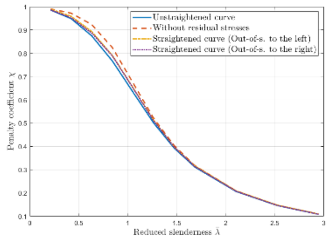


Figure 12: Residual stresses before and after balancing - reference case.

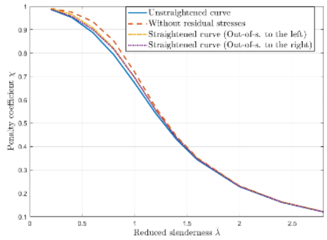
This balancing check has been performed for each residual stress distribution introduced in the software.

6.1 Buckling curves associated to the reference straightening process

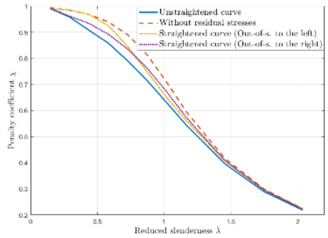
Buckling curves have been drawn by implementing those balanced residual stress patterns into the FINELG software. These curves are reported in Figure 13 for each steel profile. As a reminder, two buckling curves have been plotted as the buckling resistance depends on the initial imperfection sign as explained in Section 5.5. In addition, one last buckling curve is plotted so as to evaluate the effect of a no residual stress pattern. This last curve is useful to have an upper threshold for comparisons.



(a) HE 600 B



(b) HE 500 M



(c) HD 400 x 262

Figure 13: Buckling curves for reference-imposed displacement combination 9/6/3/0.75 mm.

As can be seen in Figure 13, the buckling resistance is higher when the initial geometric imperfection points to the left. This observation is in line with the explanation of Section 5.5.

Table 3 provides percentages which enable to quantify the benefit on buckling capacity induced by the reference straightening process. These percentages are evaluated for reduced slenderness between 0.2 and 1.5 approximately where the benefit may be contemplated. The first table column indicates the orientation of the geometrical out-of-straightness given the benefit depends on the buckling direction as already stated.

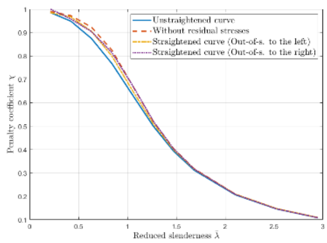
Table 3: Benefit of the reference straightening for reduced slendernesses between ≈0,2 and ≈1,5.

	HE 600 B	HE 500 M	HD 400 x 262
Out-of-st. to the left	1.91%	2,22%	4,77%
Out-of-st. to the right	1.52%	1,81%	4,35%
No residual stresses	4,16%	4,32%	9,06%

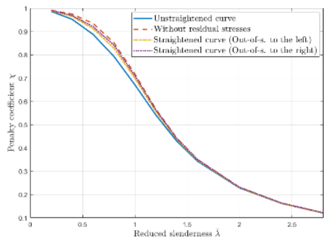
Table 3 confirms the previous visual observations. This reference combination of imposed displacements induces a benefit equal to roughly half of the one that could be obtained in total absence of residual stresses. However, as explained in Section 5.6, it is possible to find a better residual stress pattern through an optimised straightening process. This is what has been done in the following subsection.

6.2 Buckling curves associated to the "optimised" straightening process

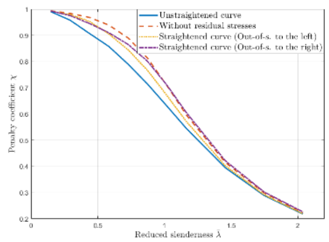
The buckling curves for the optimised straightened residual stress patterns have been established by the FINELG software in a similar way as for the reference straightened residual stress patterns. Results are reported in Figure 14.



(a) HE 600 B



(b) HE 500 M



(c) HD 400 x 262

Figure 14: Buckling curves for optimised imposed displacement combination.

As can be seen in Figure 14, the obtained curves are higher than those for reference residual stress patterns shown in Figure 13. In addition, they seem closer to the "no residual stresses" curves. In such a way to quantify this statement, benefit percentages have been evaluated for slendernesses varying roughly between 0.2 and 1.5. They are reported in Table 4.

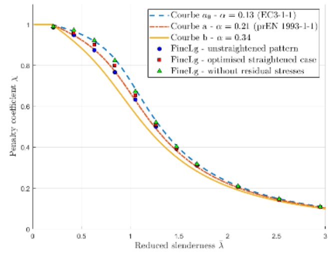
Table 4: Benefit percentages for reduced slendernesses between ≈ 0,2 and ≈ 1,5

	HE 600 B	**HE 500 M**	**HD 400 x 262**
Out-of-st. to the left	2,29%	2,50%	5,03%
Out-of-st. to the right	3,62%	3,53%	8,05%
No residual stresses	4,16%	4,32%	9,06%

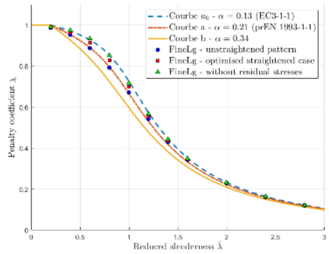
Table 4 show that the optimised residual stress patterns allow to reach buckling resistances close to the ones obtained with no residual stress patterns. This means that a refined control of the roller-straightening process could allow to maximise the buckling resistance. As a reminder, the optimised residual stress pattern considered in this subsection is based on first investigations performed in this pre-study. So, this seems to indicate that it could be possible, through detailed studies, to find an optimized setting of the straightening machine in order to enhance the buckling resistance of the straightened profiles.

6.3 European buckling curves to be adopted for straightened members in compression

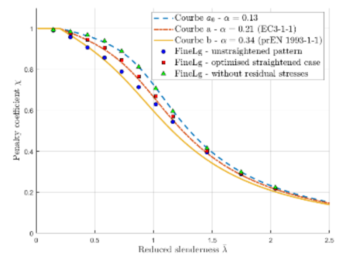
The last step of this pre-study consists in identifying whether a "jump" in the selection of the relevant European buckling curves could be contemplated as a consequence of the benefit resulting from roller-straightening process, as long as it leads to a reduction of the compression residual stresses at flange tips. The results of these buckling resistance evaluations are reported in Figure 15.



(a) HE 600 B



(b) HE 500 M



(c) HD 400 x 262

Figure 15: Simulated buckling curves versus European ones.

As explained in Section 5.5, the buckling resistances differ according to the sign of the initial geometric imperfection. In Figure 15, the minimum buckling capacity amongst both cases are conservatively reported. As shown in Figure 15, the optimised residual stress pattern for the HD 400 x 262 allows to gain one buckling curve. Unfortunately, this trend is not confirmed for the two other steel profiles. For these ones, the gain is just roughly one half a buckling curve. Just for information, the buckling curves obtained for no residual stresses would lead to the gain of one and two curves respectively for HE 600 B/HE 500 M and HD 400 x 262. These buckling curve gains are summarised in Table 5.

Table 5: Gain in terms of buckling curves depending on the residual stress pattern.

	Optimised pattern	**No residual stress pattern**
HE 600 B	1/2 → 0	1
HE 500 M	1/2 → 0	1
HD 400 x 262	1	2

On the one hand, Table 5 illustrates the fact that the residual stresses must be close to zero on HE 600 B and HE500 M flanges so as to gain one buckling curve. Depending on the level of optimisation, the curve gain varies between one half and one curve. Indeed, in order to gain more than one curve, the compression residual stresses should completely turn into tension so as to delay the buckling and to increase the buckling capacity accordingly.

Finally, the gain is higher with the HD 400 x 262 section. In fact, the gain varies between one and two curves for this steel profile depending on the optimisation level. Accordingly, a conclusion that may be drawn is that, for such large profiles, bigger positive effects could be expected through a refined optimisation of the roller-straightening process.

7 Conclusions and perspectives

The present document gathers all results of the investigations performed within this paper. It has been reported that a number of previous studies shows the potential benefit of the roller-straightening. The present work reflects today's knowledge concerning this process in terms of experimental data and theoretical approaches to simulate it.

Once the state-of-the-art is presented, a procedure to predict the residual stress distribution is chosen and detailed. Then, this procedure is used to illustrate the effect of the straightening settings on the residual stress patterns. During this work step, it has been difficult to match the theoretical distributions with experimental ones due to a lack of information concerning the way how the experimental straightening was performed.

Throughout this pre-study, two realistic distributions of residual stresses have been considered so as to evaluate the benefit resulting from roller-straightening process. The first residual stress distribution is obtained by imposed displacements taken as reference whereas the second is an "optimised" distribution based on the knowledge learned during the present research. However, a better "optimised" distribution could be found with a more specific study in which the roller-straightening process would be simulated more accurately. The establishment of residual stress distributions is performed accordingly for each of the three studied steel profiles.

The last part of the paper consists in identifying whether a "jump" in the selection of relevant European buckling curves could be contemplated when considering straightened residual stress patterns. The simulated buckling curves are established while maintaining the initial geometric imperfection equal to L/1000 as recommended by EC3. Therefore, it has been chosen to conservatively neglect the main aim of the roller-straightening which consists in straightening the steel profile. Actually, the reduction of initial imperfections increases the roller-straightening benefit.

The present work presents some encouraging results concerning the potential benefit of the roller-straightening process on residual stress distributions. For instance, an increase of one buckling curve has been observed at least with the HD 400 x 262 section in HISTAR®460 and as a reminder, the benefit is likely to be higher with lower grades which are more commonly used nowadays. As a perspective, some experimental tests should be realised in order to calibrate a numerical model and then to generate a more favourable residual stress pattern so as to take into account the beneficial impact of the roller-straightening process on column carrying capacity.

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