Methodology to Straighten the end Parts of Long Workpieces

A. Belhadj Ahmed[1], C. Baudouin[1], S. Leleu[2], R. Bigot[1], P. Secordel[3]

[1]Laboratoire de Conception Fabrication et Commande (LCFC, EA4495)

Ecole Nationale Supérieure d'Arts et Métiers, 4 rue Augustin Fresnel, 57078 METZ, CEDEX 3

[2] Arts et Métiers ParisTech, LSIS-INSM UMR CNRS 7296, 8 boulevard Louis XIV, 59046 Lille, France

[3]TATA STEEL RAIL France, 164 Rue Maréchal Foch 57700 HAYANGE
cyrille.baudouin@ensam.eu

Keywords: long workpiece, cold rolling, straightness, methodology

Abstract. A workpiece is considered as "long" when one dimension is larger than the two others, for example, railways or guides of manufacturing machines. The customers' requirements' evolutions asks the question of workpieces end parts straightness. This paper deals with the means to measure and correct the straightness, a way to prevent flaws in adapting the process and it is especially focused on improving quality for the end parts of the long workpiece. At first, to get the right measure of the straightness, we take into account the fact that the workpiece is deformable; consequently, we assumed the hypothesis that the measured straightness is composed of the intrinsic straightness and the elastic one. Then an approach was developed in order to measure any straightness. Secondly, after getting the proof that the measures are reliable; the correction of the straightness has been studied. The method of semi-automated straightening has been developed in order to improve the productivity. Some experiments have been realized and the results have been compared to the theoretical ones. The conclusions will help to find ways to modify the process in order to prevent the flaws of straightness of long workpieces.

Introduction

Long workpieces are characterized by one dimension greatly longer than the two others. Square and cylindrical cross-sections bars or rails belong to this category. These workpieces are generally produced by hot rolling process. During cooling, thermal stresses produce residual deformations evaluated through straightness error. Straightening machines with rollers are usually used to correct these geometrical variations [1, 2], but it remains straightness error at each end of the workpiece. To avoid cutting the ends [3], a loop "measuring-straightening" could be repeated up to ensure workpiece conformity. Often, end straightening is done using an hydraulic press manually driven by constraining the bar into three points bending in order to introduce a plastic deflection. Due to more and more tight requirements on straightness on the one hand, and a request to increase productivity on the other hand, the optimization of quality and time on straightening process are required. In an industrial context, in-line straightening model is desired to avoid slowing down production rates. Moreover, the success of straightening will not depend on the operator experiment.

In this work, a methodology has been developed to optimize the straightening process. This approach is based on a coupling between inspection and mechanics. First, improvements have been proposed to evaluate straightness from untreated measurements. Then, an analytical model based on elastic-plastic bending of beams was established to compute straightening parameters: distance between the press supports, load, displacement, residual deflection and springback. If the result is not good after one straightening, additional measurements should be used to improve the implemented model. To illustrate this methodology, experiments were done on square and cylindrical cross-sections bars or rails.

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In an industrial context, the proposed methodology, based on a loop "measuring - straightening", adds propositions to reduce the number of iterations to improve productivity. This paper gives some details on these specific propositions located in gray boxes on the global flow chart of straightening process (Fig. 1).

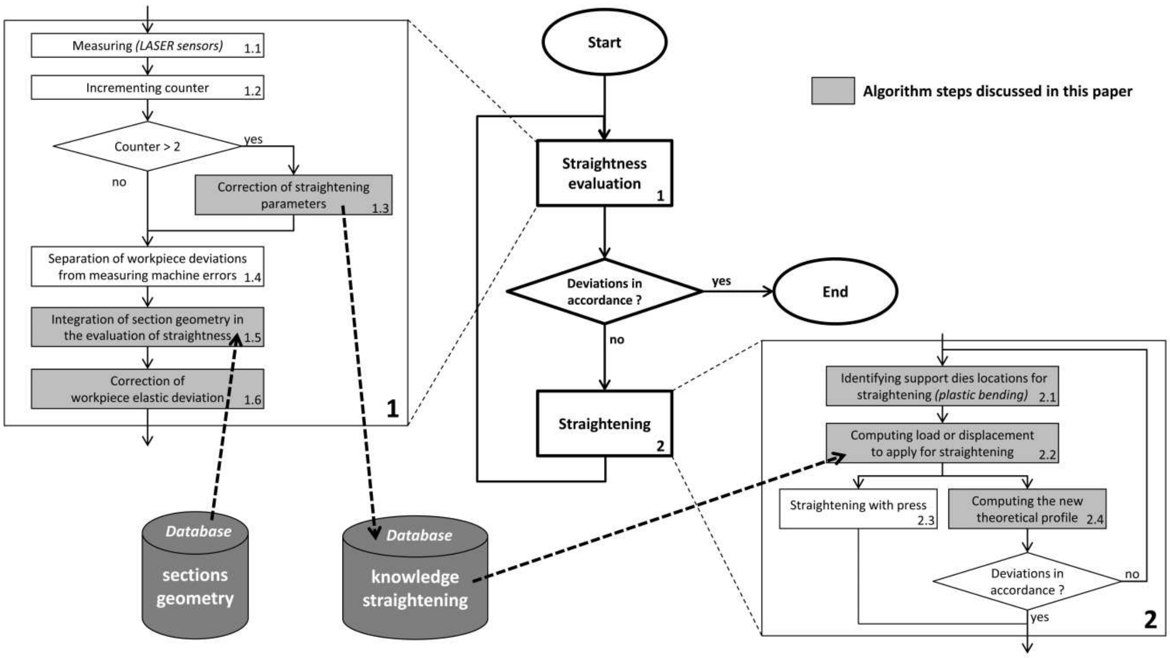


Figure. 1. Flow chart for straightening process.

The straightening of the ends of bars should be done with several press strokes if necessary, but without intermediate measurement. Only two measurements are required. The first must be done to initialize computation algorithm that will determine straightening parameters *(activities 2.1 and 2.2)*. After a first step of straightening, a second measurement is necessary to record the conformity report of controlled bar. However, if this second measurement conclude to straightness nonconformity, it will be necessary to do another loop, including, at least, a third measurement. This additional loop is considering as an unsuccess of straightening because it decreases the productivity. To ensure that this situation is not only unfavourable, the additional measurement will be treated differently than the first one in order to bring new knowledges. The third measurement not only initializes the straightening algorithm, but also its result computation will be incorporated into a database of knowledge to improve the straightening efficiency for similar configurations *(activity 1.3)*. The parameters of the material model are the principal adjustment values in the database. This activity can also be called *"improving straightening by learning*".

As finite element simulation takes too much time, an online analytical model in elastic-plastic bending is used to predict straightening parameters. Details of this model are described in mechanical straightening section. Meanwhile, during the physical straightening *(activity 2.3)*, a theoretical profile after straightening is computed *(activity 2.4).* If this computed profile remains in non-conformity, other steps of press strokes should be applied until getting a satisfying straightness. In practice, according to the profile waveform, multi-step straightening is sometimes inevitable.

The efficiency of straightening process depends on a good representation of the measured profile theoretically straight. Because of production rates requires a non-contact inspection, several technologies of measurement could be used [4]. Then, profile representation quality depends on data processing. As the product length makes it deformable and the cross-section influences the evaluation of straightness, the computation of the representative workpiece profile is discussed in next section.

Straightness of Long Workpieces

Measurement of Workpiece. The total length of evaluated workpieces is between 15 and 100 meters, the length of end parts depends both on the total length of workpiece and the distance between straightening machine rollers. Usually it should be between one and four meters. In this paper, the aim is to measure the end parts of long workpiece to evaluate its straightness. This geometric characteristic is defined as the minimum distance between two parallel lines enclosing the measured profile [5], as shown in Fig.2.

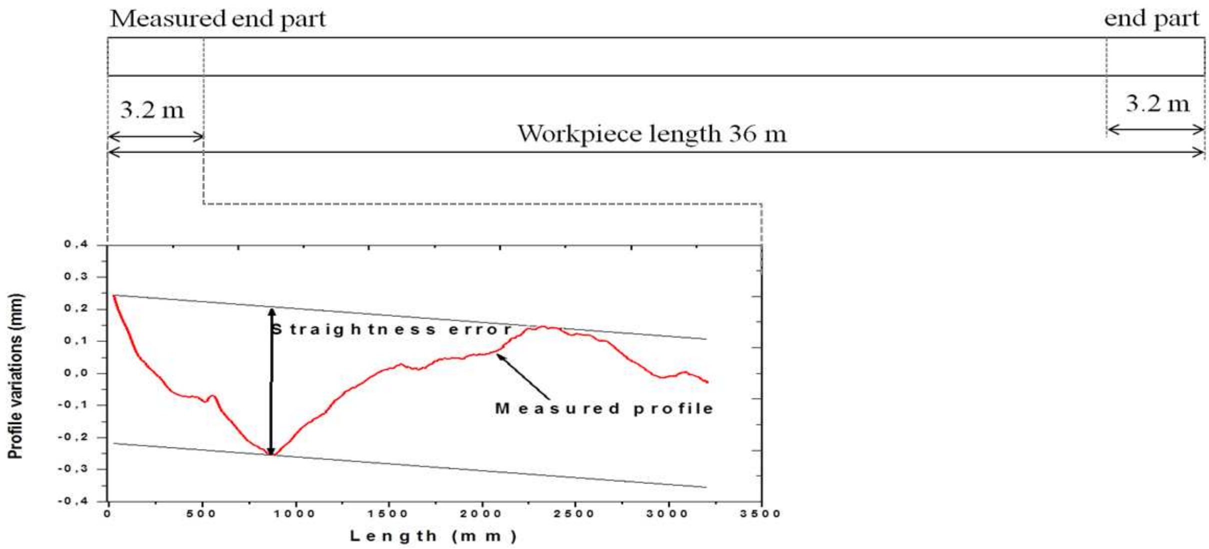
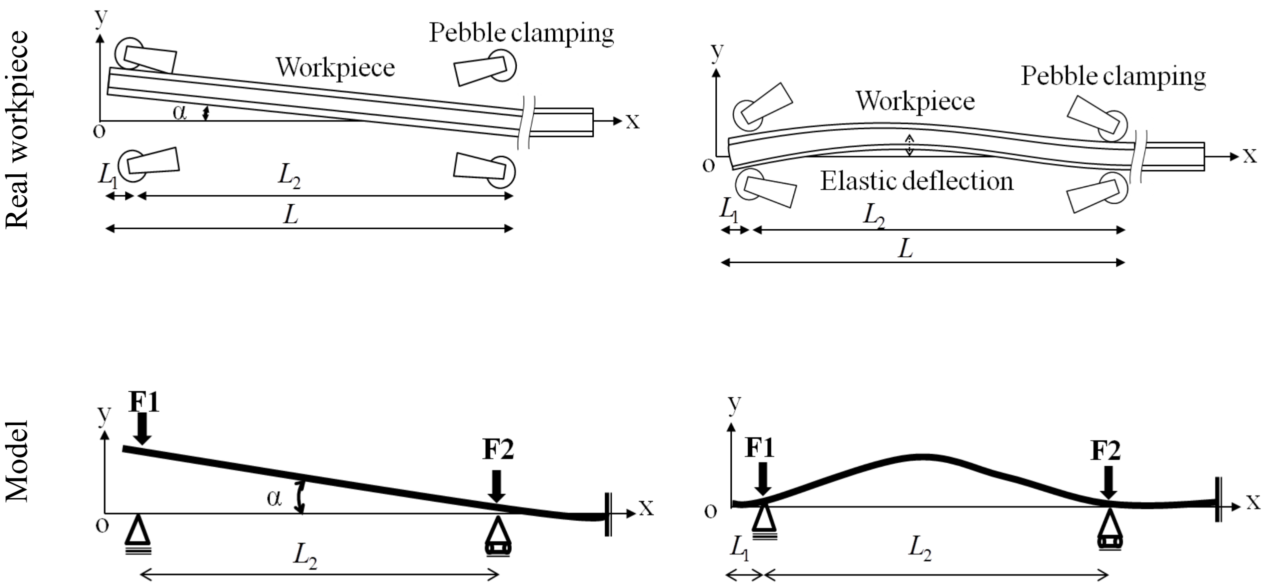


Figure. 2. Straightness evaluation of 3.2 m long end part for the workpiece of 36 m length.

Due to high evaluation length, the measurement is relatively complex. In fact, it is difficult to make accurate measuring machines with good repeatability over several meters. The best way to guarantee the conformity of such a workpiece is to control manufacturing parameters. In theory, the online control of straightening machine parameters (wear of rollers, compliant rollers positioning, load on the rollers, etc.) should be good enough to ensure straightness conformity. However, this process cannot straighten the workpiece end parts, so a specific inspection is required. Moreover, customers usually require direct inspections because they do not trust in indirect measurements. That leads to the development of particular measuring machines and associated numerical processing in order to correct imperfections: they come from mechanical guidance deviations or sensors errors (often considered insignificant). To correct mechanical guidance deviations, it is possible to design measuring machines that are able to dissociate metrological structure from that which supports the effort. As a result, obtained measurements are independent from machine components' deformation [6]. Nevertheless, this possible design increases the number of workpieces in these measuring machines (two structures, sensors to evaluate structures' deformations) so their cost too. Another way is to use a multi-probes system which makes possible to separate straightness profile of workpiece from the errors generated by measuring machine after computing [7]. However, the measure reference is done by the sensors alignment on a small length, and the smallest error could spread to the evaluated length with a large extent. Indeed the correctness and uncertainty of multi-probe scanning system is inversely proportional to the measured length and it is almost impossible to achieve high level of zero-calibration. For instance, to evaluate straightness on three meters with an accuracy of 0.3 mm, laser probe sensors must have $2.72\ 10^{-5}$mm calibration. So to make possible separation straightness profile of workpiece from the errors generated by measuring machine, workpiece must be measured in several complementary positions (reversal technique). This technique is easily applicable for the measurement of bars with a cylindrical cross-sections but it remains more complex in the case of rail, because it is not possible to rotate a long rail.

In this paper, the measuring machine considered has only one structure and uses only one laser sensor. It can be assumed that the motion deviations from the guidance system are known by an appropriate calibration carried out periodically. To evaluate straightness directly, the workpiece is motionless and sensors move along the workpiece.
The untreated measurement includes intrinsic deviations of workpiece and process measurement deviations. So, numerical computation is required to dissociate these two origins of deviations. For instance, the length of the workpiece involves hyperstatic conditions, which generates stresses on workpiece that is not in accordance with ISO 13565-1 standards [8]. In the opposite, if the workpiece is in an isostatic position on the measuring space, an elastic deformation occurs. The generated deflection is not an intrinsic error because it could be considered as a degree of freedom for the workpiece. Moreover, bad alignments of the workpiece in the measuring space could also conclude to wrong interpretations of results. The following two subsections propose methodologies to correct acquisitions errors mentioned above and related to the measurement process.
Influence of Elastic Deformation in the Evaluation of Straightness *(activity 1.6).* The measurement process begins with positioning the long workpiece in the measuring space. As a result of its length, the position in this space is uncertain. In other words, the angle α between the workpiece and the theoretical line of measurement is variable (Fig. 3).



(a) Before clamping. (b) After clamping.

Figure. 3. Elastic deviation of workpiece before and after clamping.

To achieve a reliable measurement, a laser-scanning sensor with a wide measurement field could be used to cover the workpiece during inspection as line laser sensor or a CCD camera for instance [9]. Another solution is to move the workpiece with centring touch until it was under the sensor field. The best way for a quality acquisition is to make a combination of these two solutions.
However, after moving the workpiece, it must be clamped in order to avoid elastic springback. Therefore, the inspection is done under stress. Assuming that guidance measuring machine has been cancelled *(activity 1.4)*; the measured profile is a combination of both intrinsic deviations of the workpiece and elastic curvature deviation as a result of clamping. The elastic curvature can be modelled by an elastic deflection $\delta(x)$ of beam that fits a cubic polynomial law.

$$\begin{cases} \delta(x) = K(x - L_1)(x - L_1 - L_2)(x - L_1 + L_2). & (1.1) \\ K = -\dfrac{F_1}{6EI_{GZ}}. & (1.2) \end{cases}$$

where K is constant. To separate elastic deviation from global measurement, parameter K can be minimized by least squares criterion for example. The main drawback of this methodology is the probability to accept an intrinsic cubic polynomial deviation. The effort to guarantee that workpiece is under the measurement field is linked to parameter K. So, the measurement of this effort enables to dissociate intrinsic deviations from elastic ones.

Influence of Cross-Section in the Evaluation of the Straightness. Consider a cylindrical cross-section bar perfectly straight. A laser sensor moves along this specimen according a line without deviation. If the workpiece is not correctly aligned with the inspection direction, the measured profile indicates a straightness deviation as shown in Fig.4. In fact, the inspection of a theoretical cylinder in a plane that does not include its axis generates an elliptical error. Inappropriate correction of this deviation can lead to scrap a good workpiece. Line-laser sensors or CCD camera are more adapted by measuring the highest point of each measurement to compute the straightness profile.

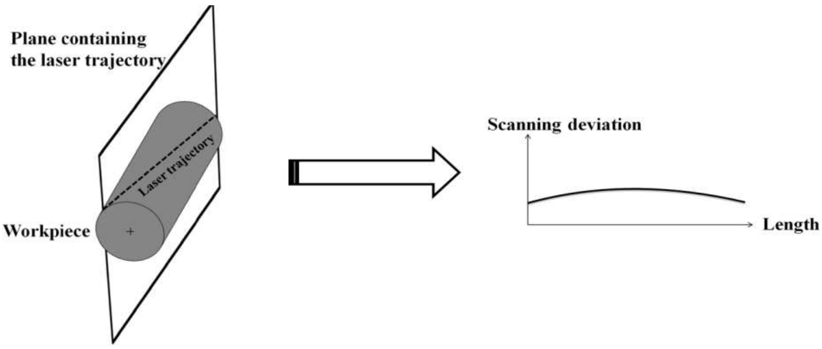


Figure. 4. Laser deviation during measurement.

In case of end parts of rail, straightness must be evaluated in the vertical and horizontal plane. Two laser sensors are oriented in these two directions and they moved to scan two orthogonal straightness profiles simultaneously. The combined analysis of the two signals could be used to correct the misalignment between workpiece and inspection direction. Indeed, two sections of a same cylindrical cross-section bar shifted in horizontal direction generate variations on laser measurement not only in the horizontal direction but also on the vertical ones (Fig. 5).

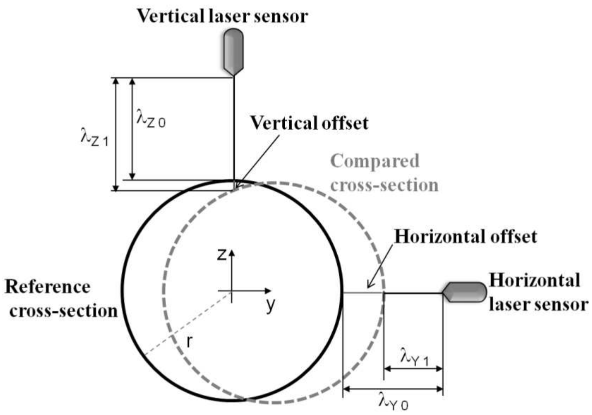


Figure. 5. Impact of horizontal offset on the vertical straightness measurement.

If the cylindrical cross-section is considered constant over the length (assumption), the impact of an horizontal shifts on vertical acquisition and vice versa leads to solve a two equations system with two unknowns: the translations in horizontal and vertical directions. For a cylindrical cross-section, the system is not linear, so numerical iterations were used to compute the representation of the workpiece profile.

Partial Conclusion. In this section, two improvements to evaluate straightness with accuracy on long workpieces were described: the elastic correction due to workpiece maintaining in the measuring space and the coupled computation with horizontal and vertical direction. Applied on the evaluation of straightness for cylindrical, rectangular and rail cross-sections, theses proposed improvements have reduced repeatability on straightness deviations by 11%.

Mechanical Straightening

Supporting Points Locations for Straightening Stroke. For each workpiece, two parallel lines enclose the measured profile *(activity 1)*, Fig. 2. There are only three points in coincidence between these two lines and the measured profile. These three points are designated as optimal support locations for bending straightening process: two are designed for supporting points and the third is designed for the controlled die. As a result, press load is not always at the middle of supporting points. However, if one of the supporting points is at the end of the profile, it should be relocated to make straightening process possible. Other critical cases could be considered:

- If the supporting points are not adjustable (commonly the press load is at the middle of supporting points), the load will be applied on the highest point of profile and supporting points are automatically located.
- If the length between the supporting points is larger than the possible setting, the load is applied on the highest point and the supporting points are positioned proportionally.

The new analytical profile is computed, even if straightening is not physically performed. If the new computed profile is not straight enough, the process described in this paragraph must be repeated several times.

Straightening Stroke Parameters. Several studies have been conducted to model the straightening process by elastic-plastic bending [10, 11]. However, in these models the relationship between load and displacement to apply for straightening in plastic range are obtained by approximated formula adjusted by numerical simulations. These models are limited by both the cross-section geometry and the material behaviour. In case of small deformations, an analytical model for the straightening process of rectangular and cylindrical cross-section bars have been developed [12]. This model takes into account only centring load between supporting points. In the present work, this model has been extended to the case of an arbitrary location of controlled die (Fig. 6).

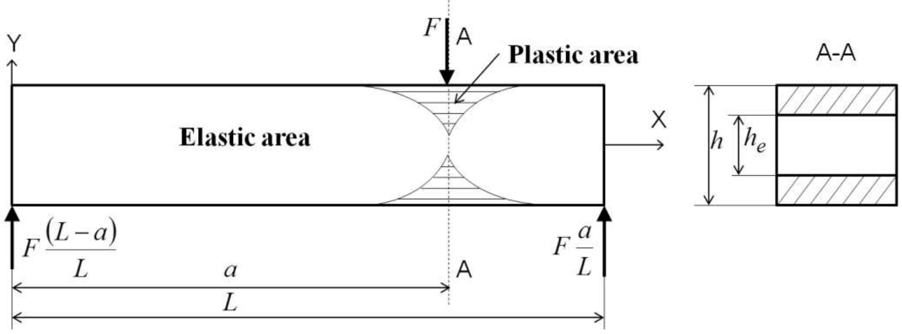


Figure. 6. Elastic plastic bending of rectangular cross-section.

The total displacement required for straightening process depends on material behaviour and on cross-section of workpiece. The material law is assumed to be elastic, perfectly plastic (no work hardening). Workpiece is stress-free and after loading only uni-axial stress is considered. During straightening, there are three stages (Fig. 7):

1. The load generates a fully elastic deformation. Under the yield load point, the displacement is proportional to the applied force. After springback, the workpiece returns to its initial state.

2. The load generates an elastic-plastic deformation: relationship between displacement and load for a square cross-section workpiece is described by Eq. 2.1 to Eq. 2.6.

$$\begin{cases} \delta_{tot} = \delta_e + \delta_p. & (2.1) \\ \delta_e = \dfrac{F\,a^2}{3\,E\,I_{GZ}\,L}\,(L-a)^2. & (2.2) \\ \delta_p = \dfrac{a^2\,M_{fy}}{3\,E\,I_{GZ}\,\tau^2}\left[5-(3+\tau).\sqrt{(3-2.\tau)}\right]. & (2.3) \\ M_{fy} = \sigma_0\,\dfrac{h^3}{6}. & (2.4) \\ I_{GZ} = \dfrac{h^4}{12}. & (2.5) \\ F = \tau\,\dfrac{L\,M_{fy}}{a\,(L-a)} \quad and \quad 1 \le \tau \le 1.5. & (2.6) \end{cases}$$

where E is Young modulus, σ_0 yield stress, I_{GZ} moment of inertia, τ coefficient that depends on the level of plastic deformation and M_{fy} bending moment at the initial yielding.

3. The load generates fully plastic deformation: a plastic hinge appears in cross-section under load location. In industrial context, this case is not considered compared to straightness deviations to reduce.

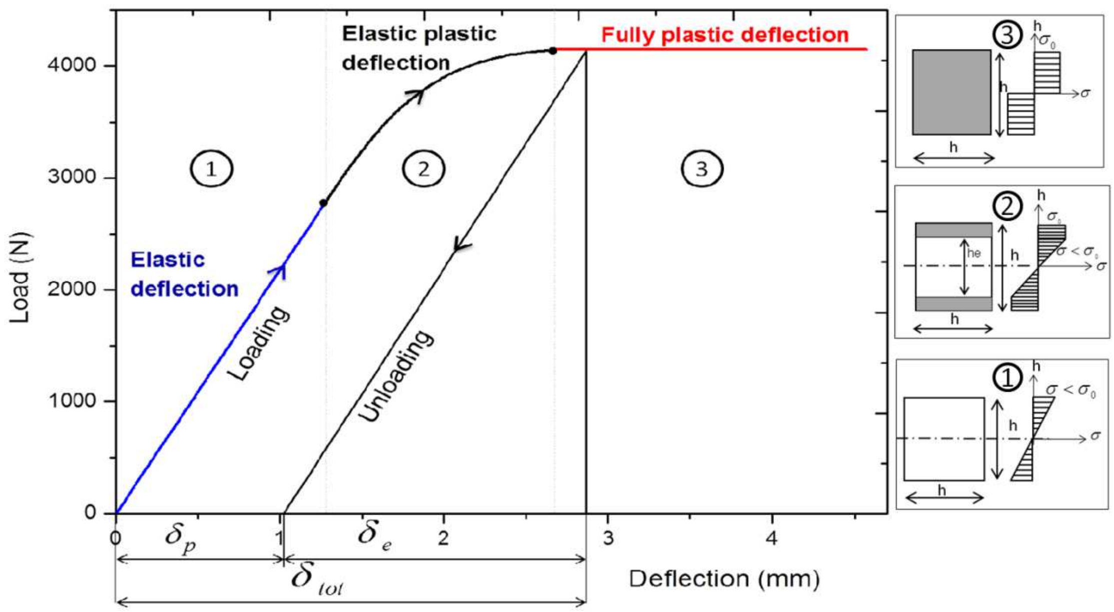
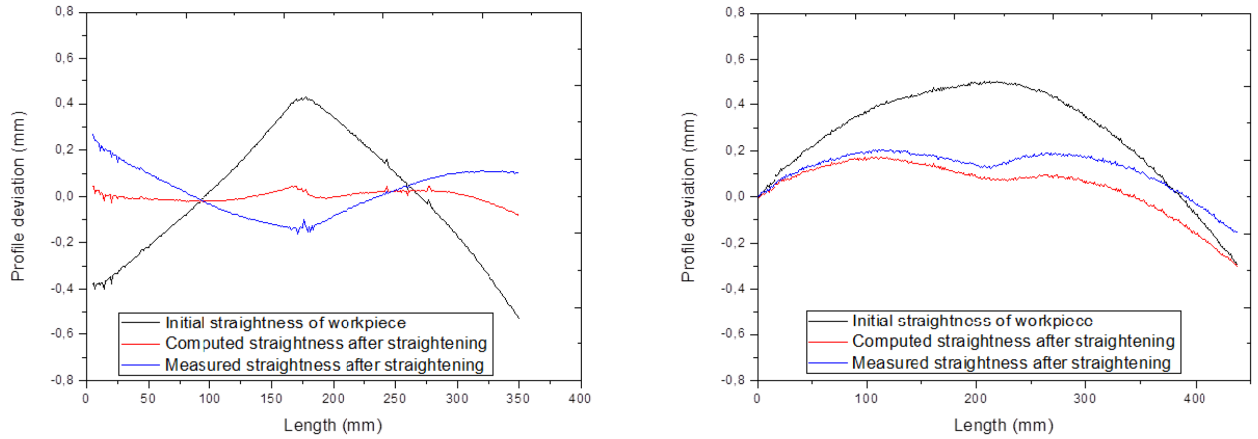


Figure. 7. Load deflection for rectangular cross-section.

The total displacement $\boldsymbol{\delta_{tot} = \delta_e + \delta_p}$ is introduced with the help of a vertical punch. After springback, the workpiece rebounds with $\boldsymbol{\delta_e}$ and the total deflection will be reduced to $\boldsymbol{\delta_p}$. If the initial deflection that has to be corrected is equal to $\boldsymbol{\delta_p}$, then the workpiece will be correctly straightened.

Results and Discussions. The methodology described in this paper was applied to straighten square cross-section bars. The Fig. 8 shows profiles of two different bars:

- In case of profiles with a large curvature, one straightening shot can reduce straightness deviation, Fig. 8 (a).
- In case of profiles with parabolic form (small) curvature, a plastic hinge appears below the load location. This case requires additional steps of straightening, Fig. 8 (b). In order to improve straightening of large curved workpiece, a model based on four points bending should be more appropriated.



(a) Large curvature. (b) Small curvature.

Figure. 8. Straightening of two square cross-section bars.

The residual stresses introduced a small deviation between computed and measured profile in the bars after straightening. This difference is computed to adjust parameters of straightening process.

Conclusion

In an industrial context, based on a coupling between mechanics and inspection, the proposed methodology describes an online process for improving straightness of long workpieces. To sum up:

- Improvements have been proposed to evaluate straightness of untreated measurements considering elastic deviations due to clamping and the influence of cross-section geometry on straightness evaluation
- Analytical model based on elastic-plastic bending of beams was established for the computation of straightening parameters: the distance between the press supports, load, displacement, residual deflection and springback.
- Two measurements *(one to evaluate residual deflection, the other to check the conformity after pressing)* should be enough to determine the straightening of an end bar. Additional measures should be taken into account to improve the implemented model in the proposed methodology.
- The experimental tests confirm that the methodology described in this paper would be of considerable help to the operator or even can be automated to improve productivity.

Acknowledgements

Authors would like to thank Tata Steel Rail France and the region “Lorraine” for their technical and financial contributions.

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