Numerical modelling of sheet metal guillotining process

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Abstract
This work is focused on the numerical analysis of sheet metal guillotining process aimed to evaluate relevant shearing force as well as the final configuration of the sheet. In the first part of the paper a new approach, based on a 2D plane strain simulation performed on Simufact.Forming 10.01 GUI, is proposed to estimate the shearing force. Afterwards the final configuration of the sheet is predicted adopting a 3D FE simulation of the guillotining process (in this case the FE code Simufact.Forming 10.0.1 GP was adopted).

1. Introduction
Guillotining is a sheet metal cutting process, in which the sheet is cut progressively from one end to the other. Guillotining should be considered a 3D forming process, which includes the progressive straight cut of the metal sheet. In principle the FE model should includes the 3D models of the tooling including the blank holder and the 3D model of the sheet; the material behaviour is anisotropic elastoplastic with non linear strain hardening coupled with ductile damage under large plastic deformation. These requirements lead to a very complex FE simulation where a specific procedure should be implemented in order to eliminate the mesh elements when they reach the critical level of damage during the shearing process [1 - 3]. A high number of elements to predict the correct geometry of cut border is required and the computational time increases to an unacceptable level.

To overcome these limits a simplified approach based on Simufact Forming 10.0.1 is proposed to predict the shearing force. The simplified model is based on a 2D plane strain simulation of the shearing process including the elimination of 2D mesh elements when damage reaches the critical level. The results in terms of shearing force are converted as function of the sheared thickness depending on the geometry of the shearing blade and integrated in order to estimate the required cutting force during the guillotining process. The first part of the paper details the proposed procedure which can be adopted only to predict the shearing force and the twisting angle.

The prediction of the final configuration of the sheet requires a 3D FE simulation which is described in the second part of the paper. Results in terms of final geometry of the sheet after guillotining are presented. Moreover a comparison between the shearing force and the
twisting angle predicted by the 3D simulation and the force and angle predicted adopting the simplified model was performed. The comparison indicates that the proposed approach based on a 2D plane strain simulation can be adopted to predict shearing force of the guillotining process with a considerable saving of computational time.

2. The guillotining process
In Figure 1 is presented a schematic view of the guillotining process.

![Figure 1. Scheme of the guillotining process.](image)

Geometrical properties of the sheet (length, width and thickness) and the guillotining tools (rake angle, radius and clearance) are summarized in Table 1. The upper knife moves downwards with a constant displacement rate of 128 mm/s. The sheet is made of AISI 304.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Width</th>
<th>Length</th>
<th>Radius</th>
<th>Clearance</th>
<th>Rake angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 mm</td>
<td>100 mm</td>
<td>50 mm</td>
<td>0.002 mm</td>
<td>0.237 mm</td>
<td>3°</td>
</tr>
</tbody>
</table>

3. Prediction of shearing force
The guillotining process is a 3D shearing process where the cutting force is almost constant during most of the cut if the beginning and the end of the process are neglected. In the initial part of the cutting operation the tool is gradually entering in the thickness of the sheet and the portion of the deformed material is increasing from 0 to a final value which depends on the thickness of the sheet and on the inclination angle of the blade. When the cutting tool reaches the thickness of the sheet the process become to be stationary until it approaches
the end of the cut where the phenomenon is similar but the decrement of the portion of material from a maximum to 0 has to be considered.

The inclination angle of the blade is usually limited to 1-5 ° and, as an acceptable hypothesis, the material is deformed in conditions which are not far from the plane strain condition [4]. Under this hypothesis the process can be modelled as a 2D plane strain process, which is a very simple and computationally efficient model.

![Force vs Upper knife displacement graph](image)

**Figure 2. Upper knife Z- Force predicted by plain-strain model.**

The resulting vertical force applied to the cutting tool as predicted by the model is represented in Figure 2. As the upper knife advances, the force increases until it reaches the maximum value due to strain hardening of the sheet. Then it decreases because of the reduced neck area in the sheet, where shearing resistance of the sheet acts. After the punch load reaches the maximum value, the upper knife advances without increase of its load. At this moment the neck area reduces rapidly causing the complete fracture very soon. This is one way to determine the penetration depth for the investigated process [4]. The 2D simulation predicts that the penetration depth is estimated at 2.6 mm of upper knife advance (as shown in Figure 2). The Cockroft-Latham’s damage distribution was then analyzed when the upper knife displacement reaches the value of 2.6 mm (Figure 3). The maximum accumulated damage occurs at the top and bottom surfaces contacting the sharp corner of the upper and lower knife, respectively. The maximum value predicted by simulation is about 2 and therefore it was assumed that the critical damage value for the investigated material is 2.
Figure 3. Upper knife Z-Force predicted by plain-strain model.

The vertical force applied to the cutting tool as predicted by the model divided by the width of plane-strain model represents the unitary force relevant to deformation at the corresponding depth of penetration of the tool in the thickness of the sheet.

For this reason each point of the curve of Figure 2 can be mapped to a new point defined by the following relationships (1) and (2)

\[ F_{\text{NEW},j} = \frac{F_{\text{ORIG},j}}{\text{Width}_{\text{plane}_{\text{strain}}}} \]  
\[ x_j = \frac{\text{Stroke}_j}{\frac{1}{\text{tg}(\alpha)}} \]

(1)

(2)

The new curve obtained as described above represents the contribution to the cutting force of a \( dx \) portion of material involved in the guillotining process. Therefore the cutting force (3) required can be estimated as the area below this curve calculated from 0 to \( X_{\text{fin}} \) defined as

\[ F_{\text{guillotining}} = \int_0^{X_{\text{fin}}} F_{\text{NEW}} \, dx \]  

(3)

where

\[ x_{\text{fin}} = \text{depth}_{\text{in}} \frac{1}{\text{tg}(\alpha)} \leq \text{thickness} \frac{1}{\text{tg}(\alpha)} \]
The curve relevant to Z force applied by the knife obtained with this mapping of data is compared with the corresponding curve predicted by the 3D model in Figure 8. Moreover the twisting of cut sheet has been estimated in the 2D model as the angle of rotation of the undeformed part of the sheet as shown in Figure 4 and resulted to be 20.68° at the end of the shearing.

**Figure 4. Equivalent plastic strain at the end of the cutting in plain-strain model (left) and estimation of twisting angle (β) (right).**

The plot of this angle shown in the same figure for the different penetration of the knife in the plain strain model presents an initial linear slope followed by a constant value just after the critical depth of 2.6 mm is reached. These results should be carefully examined because the transposition of these conclusions in 3D is not straightforward: the cross section of the cut strip stops its twisting after 2.8 mm of penetration of the knife, but the other sections present in the 3D model also rotate by a quantity which depends on the distance of the section from the beginning of cutting phenomenon.

The diagram suggests that a linear relationship can be reasonably adopted and therefore the contribution of the rotations of the different sections can be estimated as ½ of the final rotation predicted by the plain strain model which should be added to the twist rotation as predicted by plain strain model. We should expect a twisting angle around 31.03° in the 3D model.
4. 3D FE simulation of the guillotining process
The guillotining process was numerically simulated using the FE code Simufact.forming GP 10.0.1 (based on Marc2010 solver). The mechanical analyses were performed adopting a 3D model of the guillotining process.
Tetrahedral Herrmann elements (type 157) having a size of 2 mm was used in the analysis. MSC.Patran tetra mesher was used for the meshing. To improve meshing, a local refinement box with level 3 was defined in the region where contact between sheet and upper knife takes place. The number of elements used to mesh the sheet is about 50000.
The element distortion, tool penetration and strain change (0.4) criteria were used to determine when remeshing should be performed.
The sheet was assumed to be isotropic and elasto-plastic. The constitutive model adopted was based on a Von Mises yield surface. The material has a Young's modulus of 193 GPa, a Poisson's ratio of 0.28 (elastic) and a yield strength of 90 MPa.
Material rheological behaviour was simulated according to the Hollomon constitutive model (4). It represents the flow stress as:

\[ \sigma_f = k \cdot \varepsilon^n \]  

(4)

where \( \varepsilon \) is the deformation (total strain), \( k \) is the hardening coefficient and \( n \) is a sensitivity to strain hardening term.
The material constants were obtained from the material library of Simufact.Forming. The strain hardening relationship is:

\[ \sigma_f = 1451 \cdot \varepsilon^{0.6} \]  

(5)

In order to reduce the computation time, the tools were modelled as rigid. Coulomb law was used to model the shear stress due to the effect of friction on the upper knife, lower knife and blank-holder.
The friction coefficient \( \mu \) at the interface between sheet and upper and lower knife was chosen equal to 0.05, at the interface between sheet and blank-holder 0.2.
The damage criterion Cockroft-Latham was activated in order to examine the ductile damage level as well as to visualized the crack initiation and propagation. The element removal threshold was chosen equal to 2 as described in the previous section.
The adaptive time stepping procedure auto step was used in the simulation. The 3D model of the guillotining process is shown in Figure 5. Some results of the simulation at the beginning and at the end of the guillotining process are shown in Figure 6.

The final configuration of the sheet is shown in Figure 7. In this figure it is possible to note the torque effect presents in the sheet after guillotining. Measuring the twisting angle $\beta$ on the geometry predicted by the 3D model at the beginning of separation of the stripe we obtain a value of 31.58 °, with an absolute error of the 2D estimation below 1°.
Figure 7. Total equivalent plastic strain. Upper knife displacement 6.6 mm (steady state stage of the guillotining process). Torque effect in the configuration of the sheet is also evidenced.

Figure 8 shows the evolution of the guillotining force versus the upper knife penetration. In the figure are also reported some deformed configurations of the sheet. Looking at the evolution of cutting force three phases can be identified.

1. In the first phase (OA) the guillotining force increases until $F_{\text{max}} = 134$ kN corresponding to the maximum force of the whole process. The quantity of deformed material increases from 0 to a maximum corresponding to the penetration of the knife in the whole thickness of the sheet.

2. In the second phase (AB), the force decreases from 134 to 130 kN corresponding to the crack initiation and propagation in the sheet cross-section.

3. The third stage can be identified from points B to C. It is characterized by a quasi-constant guillotining force indicating the steady state stage of the guillotining process. The average value of force in this phase is $F_{\text{sta}} = 127$ kN. The analytical calculation of this stationary force described in the previous section gives $F_{\text{sta}} = 123$ kN which is 3 % lower than the value predicted by the 3D numerical simulation.
5. Conclusions

The paper describes the numerical analysis of sheet metal guillotining process aimed to evaluate relevant shearing force as well as the final configuration of the sheet. A simplified approach is proposed to predict the shearing force. The simplified model is based on a 2D plane strain simulation of the shearing process including the elimination of 2D mesh elements when damage reaches the critical level. The results in terms of shearing force are converted as function of the sheared thickness depending on the geometry of the shearing blade and integrated in order to estimate the required cutting force during the guillotining process.

The prediction of the final configuration of the sheet is performed adopting a 3D FE simulation. The damage criterion Cockroft-Latham was activated in order to examine the ductile damage level as well as to visualize the crack initiation and propagation. The results of the simulation evidenced the torque effect in the final configuration of the sheet after guillotining.

Moreover a comparison between the shearing force and the twisting angle predicted by the 3D simulation and the force and angle predicted adopting the simplified model was performed. The comparison indicates that the proposed approach based on a 2D plane strain simulation can be adopted to predict shearing force of the guillotining process with a considerable saving of computational time.
References


