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On the Deformation Modes of Continuous Bending under Tension Test

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Abstract

In this paper the continuous bending under tension (CBT) test is analyzed by numerical simulation. In CBT test, the material is deformed to high level of strain that is beyond the achieved strain by the standard tensile test. The main stability criterion describes the importance of compressive stress produced by bending in stabilizing the deformation. At the symmetry line of the strip, the material can be assumed simply to deform by bending and stretching in plane strain condition. The focus of this paper is to study the deformation modes through thickness at the symmetry line. It is found that the material experiences three deformations modes. The cyclic parts through thickness experiences two deformation modes: the first is limited between uniaxial tension and plane strain and the second deformation mode is limited between pure shear and uniaxial compression. The third deformation mode is observed at the middle part through thickness and it is based on tension and the contribution of through thickness stress.

Keywords: bending under tension; deformation mode

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1. Introduction

The continuous bending under tension (CBT) test can be seen as a tensile test on strip material with additional bending by a set of rolls that is traveling over the length of the strip. The main effect of additional bending is that the required tensile force for the same elongation is reduced [1]. The CBT test was proposed as a method for increasing elongation to investigate material properties at high levels of straining [2]. The deformation around rolls in the CBT test bears resemblance with the deformation around the spherical tool in incremental sheet forming (ISF). This resemblance motivated Hadoush et al to present a 2-dimensional finite element model for the CBT test as a simplified test of ISF process [3]. The main focus was to study the contribution of bending in stabilizing the deformation of a strip to high strain. Experimentally, Emmens and Boogaard showed that high levels of strain are obtained for various materials using CBT test [4]. Also, the CBT test is identified as incremental forming process because the strip, that is used in CBT test, is deformed incrementally rather than continuously as in a standard tensile test, the proposed CBT setup by Emmens and Boogaard is shown in figure 1.


Figure 1: CBT setup [4].

CBT test is a simple test to perform but many aspects of the test have not been investigated yet e.g. deformation modes during the test. Hadoush et al. present a numerical investigation, focusing on the process description, to analyze the obtained cyclic force-displacement curve of CBT test [5]. It is concluded that the cyclic force-displacement curve consists of two parts: a steady part and a transient part (peak). A simple mechanical model incorporating non-constant bending radius and cyclic material behaviour is presented in [6] in addition to an extensive overview on stability and formability of CBT test.

The focus of this work is to study the deformation modes during continuous bending under tension. Numerically, part of the CBT test is simulated which mimics qualitatively half cycle of the process. The stress

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evolution near the symmetry line of the strip, in longitudinal direction, is recorded and analyzed to investigate the variation of the deformation modes through the thickness of the strip.

2. CBT Test

The experimental description of the CBT test has been explained in detail in [4]. Within this section, some of the experimental descriptions will be mentioned for their relations to the numerical model. The CBT setup is shown in figure 1. The roll set consists of 3 frictionless cylinders of 15 mm diameter. In longitudinal direction, the rolls are separated from each other by 17.5 mm. The roll set can travel in the longitudinal direction only. First, the central roll is placed such as to fit the specimen in between the rolls without deforming it. Then the central roll can move in thickness direction to introduce bending. A two dimensional schematic of the FE model is shown in figure 2.

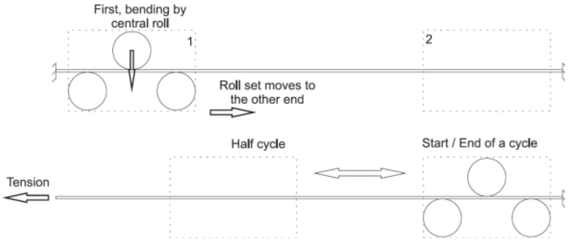
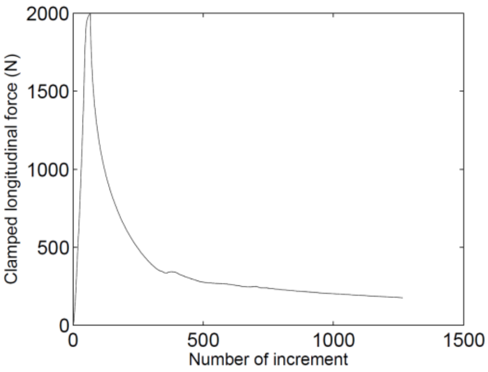


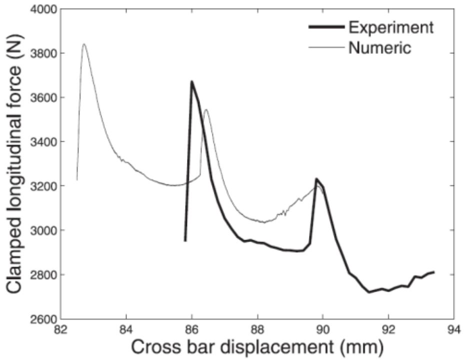
Figure 2: Continuous bending under tension process description.

The bending in the specimen is introduced by the movement of the central roll downwards. The movement of the roll set in longitudinal direction introduces the bending in a cyclic manner.

The left edge of strip, as shown in figure 2, is fixed to the cross bar of the tensile machine while the right edge of the strip is fixed to stationary part of machine. At the beginning of CBT test, the bending is introduced then the roll set is moved from left to right with zero displacement of the cross bar. After this initial part, the current position of the roll set defines the starting point of the cycle, the roll set starts traveling forward 'left' and backward 'right' performing one cycle and so on. In this work, the initial stage of the CBT test is considered only because it mimics qualitatively half cycle of the process. The clamped longitudinal force for both the initial stage and for one cycle is shown in figure 3. During the cycle, the cross bar movement introduces tension. In the initial stage, the strip has to stretch to follow the curved geometry of the roll set and this introduces the tension. The movement of the roll set introduces the bending in cyclic manner in both cases.



(a) Initial stage.



(b) One cycle.

Figure 3: The clamped longitudinal force a) The initial stage as predicted in this work b) One cycle with experimental verification [5].

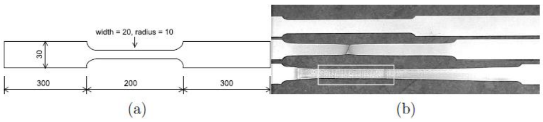
3. Numerical model

The used specimen in CBT test is shown in figure 4a. Through the length of the specimen, the specimen has uniform thickness and piecewise uniform width. The cyclic bending is performed only in the middle part of the specimen. Experimentally, it is observed that the part that experiences the combined tension and bending deforms as shown in figure 4b. The plastic deformation of the wider parts is neglected and a rigid body motion of these parts can be assumed for mild steel. Only the middle part of the specimen is considered in the simulation. Because of symmetry along the longitudinal axis, half of the middle part of the specimen is modeled. The modeled part of the specimen is 200 mm in length and 10 mm in width. The thickness of the modeled part of the sheet is 1 mm. A regular mesh made of solid-shell element is used to discretize the geometry of the strip, the 200 mm length is discretized by 2000 element, the 10 mm width is discretized by 10 element and one element through thickness. The solid shell element is based on enhanced assumed strain and modified assumed natural strain methods for one-point quadrature solid-shell, the element is called MRESS [7]. MRESS element has an eight-node brick topology, three displacement degrees of freedom per node. MRESS has one integration point in-plane and a flexible number of integration points can be used through thickness, here, seven integration points are used.

The material model is kept as simple as possible. The isotropic yield behavior of the material is modeled with the von Mises criterion. The work hardening is governed by linear relation:

$$\sigma = 200 + 500\varepsilon$$

Where σ and ε are the flow stress and equivalent plastic strain, respectively. The material has a Young's modulus of 200 GPa and Poisson's ratio of 0.3. For experimental verification, it is acknowledge that a better material model is required that includes e.g. the anisotropic behavior of the sheet and a nonlinear work hardening model.



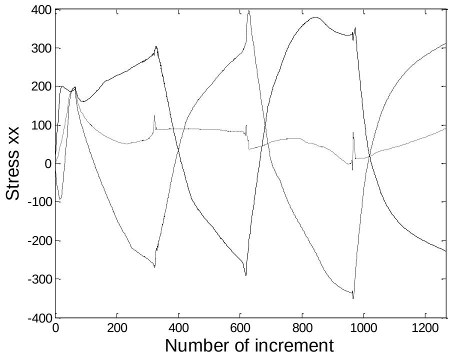
(a) (b)

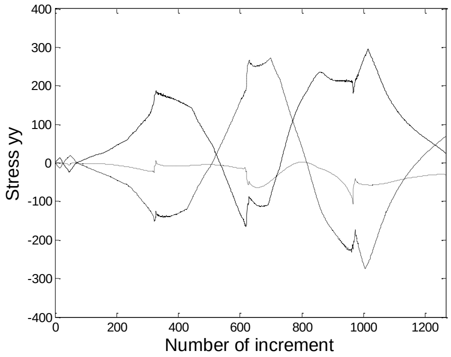
Figure 4: Specimen of CBT test a) Schematic of the specimen, dimension is in mm and the drawing is not to scale b) Unused and used specimens: untested (top), tensile tested (middle) and CBT tested (bottom). A uniform deformation is observed in the white rectangle [4].

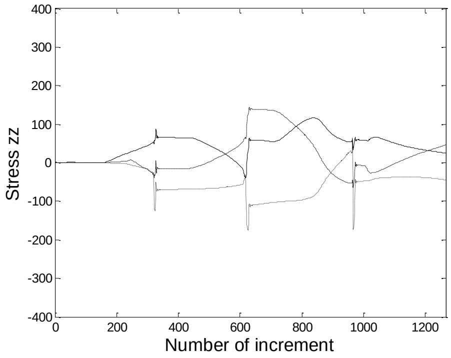
4. Results and Discussion

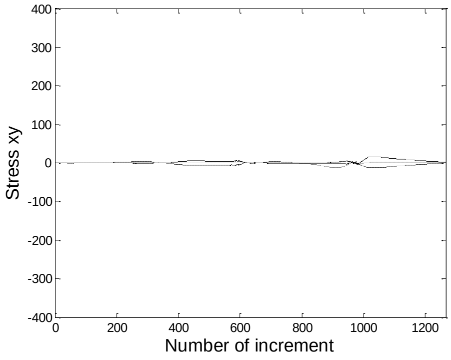
In CBT test, a material portion has to be deformed by two sets of bend-unbend-bend in order to experience one complete cycle. Here, bending term is used to refer to bending by lower rolls while unbending is used to refer to bending by central roll. The material portion has to be straightened each time the strip changes its curvature direction from bending-unbending and from unbending-bending. In this demonstration, the roll set will moves 60 mm from its initial position to the right and this will mimic half cycle of CBT test. A finite element simulation is performed. The stresses are recorded for a particular location that is originally 5 mm to the right of the roll set at its initial location and it will be 5 mm to the left of the roll set at the end of its movement. This location is as close to symmetry section in longitudinal direction of the strip.

The predicted stress components are plotted in figure 5, these stresses are global stresses. The first observation to mention is that the achieved values of the shear stresses are almost negligible compared to the achieved values of the normal stresses. Focusing on the order of the normal stresses, the longitudinal stress σ_{xx} is the major stress component then σ_{yy} through width. The normal stress through thickness σ_{zz} ratio to σ_{xx} has an order of one to four. Based on this observation, It can be assumed that the normal stresses coincide with the principal stresses with acceptable margin of error. Actually, σ_{xx} and σ_{zz} can be rotated around y-axis, transformed, so that it results in reducing through thickness stress to zero except when the surface has contact with the rolls.









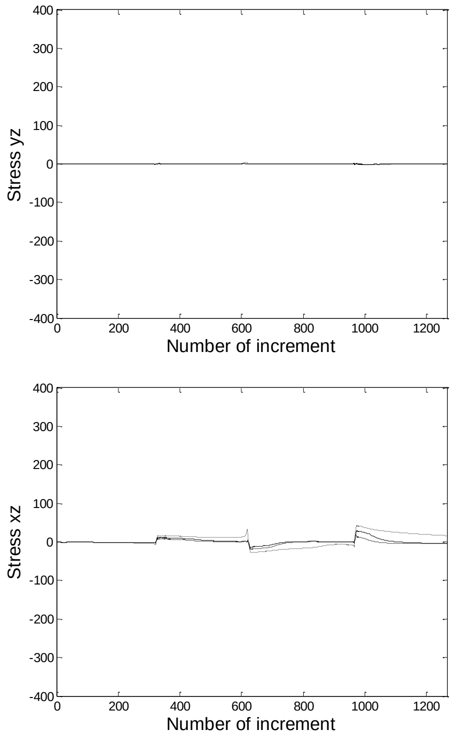
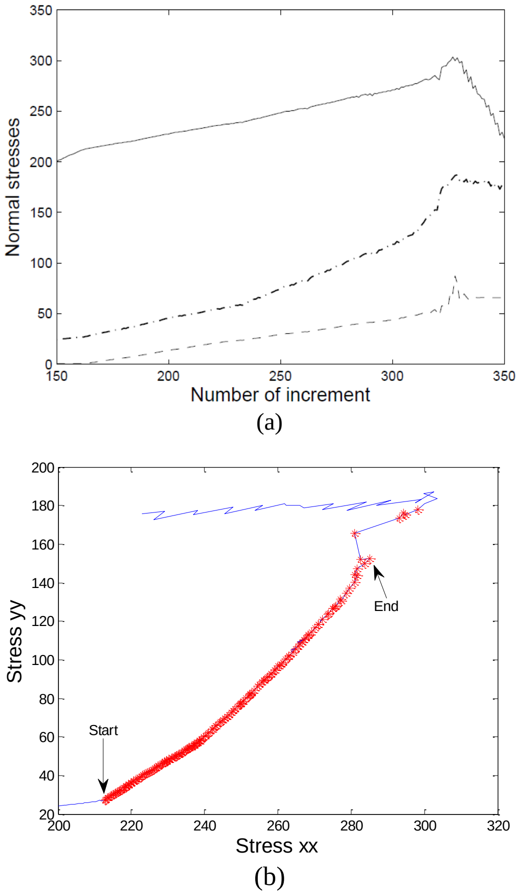


Figure 5: Stress state evolution through thickness: upper (solid line), mid (dotted line) and lower integration point (dashed line).

Prior to increment 166, the studied material portion is in tension and it is outside the roll set zone. It is bent by the right lower roll Between increment 167-466, the top surface is in tension while the bottom surface is in compression because of bending. In addition, the entire strip is under tension, therefore, the top surface has a higher stress value compared to the value of the stress at the bottom surface. This situation is flipped when the material portion experiences the central roll, it is unbent. At this stage, the material experiences the smallest radius of curvature that is larger than the radius of the roll, therefore, the bottom surface reaches a higher level of stress than the achieved level at the top surface. The longitudinal stress σ_{xx} at mid-plane is always in tension for the entire history of the process. The introduced plastic deformation will reduce the tension in the strip, this results in reducing the achieved value of the longitudinal stress when the strip is bent by the lower roll. The stress state that results in producing the plastic deformation will be the topic of the following discussion.

The material portion experiences different deformation modes when it passes the roll set. Mainly, three deformation modes are identified, two of these deformation modes (I and II) are observed in the material layers, through thickness, that are deformed by cyclic loading. The third deformation mode III is observed in mid-plane that is monotonically loaded in tension. The material portion is deformed by deformation mode I when it is bent or unbent by the rolls, a sample of the normal stresses evolution during this mode is plotted in figure 6. This deformation mode is characterized by: the normal stresses have the same sign, σ_{xx} has the largest achieved value followed by σ_{yy} then σ_{zz}, the magnitude of $\sigma_{xx} - \sigma_{yy}$ decreases, $\sigma_{yy} - \sigma_{zz}$ increases and $\sigma_{zz} - \sigma_{xx}$ increases. In case of ignoring σ_{zz}, or assuming plane stress condition, and defining α as the ratio of σ_{yy} to σ_{xx}, it is observed that the material is deformed plastically starting from a deformation mode close to uniaxial deformation in tension α = 0.128 and shifts continuously toward a deformation mode close to plane strain α = 0.54 as plotted in figure 6b. Keep in mind that in plane stress condition α = 0 indicates uniaxial deformation, α = 0.5 indicates plane strain, α = 1 indicates biaxial stretching and α = -1 indicates pure shear.

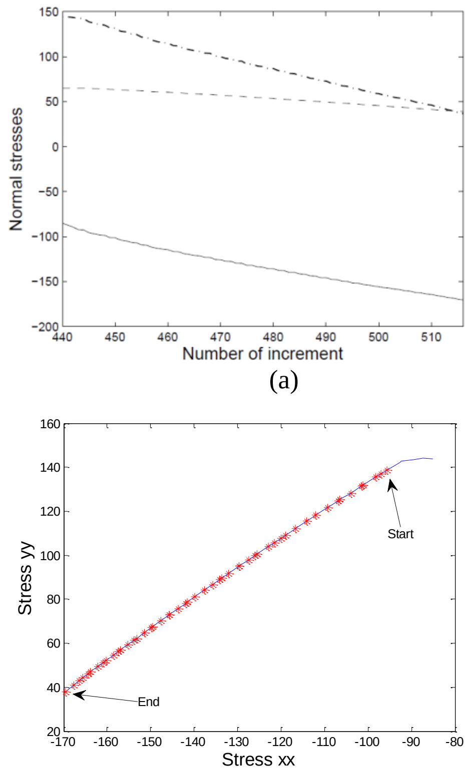


(a)

(b)

Figure 6: Deformation mode I a) Normal stresses: σxx (solid line), σyy (dashed line) and σzz (dashed-dotted line). b) Yield surface, marker indicates plastic deformation.

The material portion experiences deformation mode II when it is straightened, a sample of the normal stresses evolution during this mode is plotted in figure 7. The main characteristics of this deformation mode are: the normal stress σ_{xx} is negative while σ_{yy} and σ_{zz} are positive, the magnitude of $\sigma_{xx} - \sigma_{yy}$ decreases, $\sigma_{yy} - \sigma_{zz}$ decreases, $\sigma_{zz} - \sigma_{xx}$ increases. With similar simplification as made in deformation mode I, it can be considered that the material starts deforming plastically from a deformation mode near pure shear with α=-1.45 passing the point of pure shear to uniaxial deformation in compression at α =-0.215 as shown in figure 7b.



(a)

(b)

Figure 7: Deformation mode II a) Normal stresses: σxx (solid line), σyy (dashed line) and σzz (dashed-dotted line). b) Yield surface, marker indicates plastic deformation.

Deformation mode III is observed only in the mid-plane when the material is bent or unbent, it is loaded in tension. Prior to the plastic deformation, a sudden increase of σ_{xx} and a sudden decrease of σ_{zz} are observed, a sample of the normal stresses evolution during this mode is plotted in figure 8. The deformation mode is characterized by: the normal stress σ_{xx} is positive while σ_{yy} and σ_{zz} are negative, the magnitude of $\sigma_{xx} - \sigma_{yy}$ decreases, $\sigma_{yy} - \sigma_{zz}$ increases, $\sigma_{zz} - \sigma_{xx}$ increases. It is observed that the material deforms plastically in tension at a low value of σ_{xx} because of the contribution of σ_{zz}. Keep in mind that Boogaard et al. concluded that through thickness stress, contact stress, reduces the yield stress in tension if it bends over some radius [8].

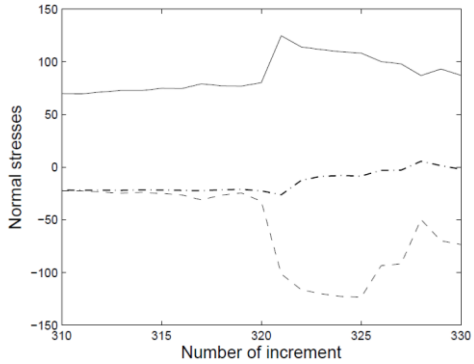


Figure 8: Normal stresses of deformation mode III: σxx (solid line), σyy (dashed line) and σzz (dashed-dotted line).

5. Conclusions

In this work, the continuous bending under tension is studied focusing on the stress state at the symmetry line along the longitudinal direction of the strip. It is observed numerically that the value of shear stresses are almost negligible compared to the value of the normal stresses. Three deformation modes are identified, two of these deformation modes (I and II) are observed in the material layers that are deformed by cyclic loading. The third deformation mode III is observed in mid-plane that is monotonically loaded in tension. Deformation mode I is active when the material is bent or unbent and it varies from uniaxial deformation in tension to plane strain. Deformation mode II deforms the material starting from pure shear mode to uniaxial deformation in compression and it is active when the material is straightened between the rolls. The third deformation mode is observed in the mid-plane through thickness and it is based on the contribution of thickness stress in reducing the required tension to plastically deform the material when it is bent. The focus of future work is to study the variation of the deformation modes through the width of the strip in CBT test incorporating anisotropic material model. The variation of deformation modes for the entire cross section, that is perpendicular to longitudinal direction, may provide a better understanding of how the deformation of material is stabilized to achieve high strain.

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