Fundamental Differences between Fracture Behavior of Thin Sheets under Plane Strain Bending and Tension

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Abstract: A numerical investigation of thin sheets under plane strain tension and bending is presented. Bending simulations are based on a VDA plane-strain bending test while tensile simulations depict a notched plane-strain tensile coupon. A comparative analysis of the stress and strain distributions inside the localized zone of deformation is performed for two investigated modes of behavior. The analyses suggests significant stress state differences in bending and tension driven primarily by the through-thickness response. The results offer insight into fundamental differences in tensile and bending fracture behaviors of thin sheets, as evidenced by discrepancies in strain at fracture experimentally measured using notched tensile coupons comparing to VDA bend tests. The consequences of these differences for material characterization and model calibration for large-scale crash simulations are also briefly discussed.

1. Introduction
Recent experimental studies (Bandpay [1], Butcher and Dykeman [2], Cheong et al. [3]) showed a consistent trend of higher strain at fracture measured under plane-strain bending loading than those measured under plane-strain membrane (or in-plane) tensile loads. In the former case, the experiments are usually conducted using the VDA238-100 test procedure [6], where a wide sheet is subjected to three-point bending with the load applied by a wide indenter and a tip radius ranging from 0.1-4mm. The test setup, shown in Figure 1a, causes the sheet to completely fold on itself resulting in high tensile strains on the bottom of the sheet. In addition, relatively large width of the specimen and compression on the top prevent deformation in the width direction forcing a plane strain condition. The traditional plane strain tensile tests rely on a notched specimen with a wide gauge sections that induces plane-strain state. The membrane (or in-plane) plane strain tensile specimen used here is shown in Figure 1b.
Since both test setups generate nominally the same stress state (under the assumption of plane stress), they could be expected to produce approximately the same strain at fracture (with everything else being equal). This is however not the case as evidenced by multiple experimental results, including a recent study of DP980 steel performed by Butcher and Dykeman [2] (Figure 2).

**Figure 1.** Plane strain tensile tests: a) VDA bending test setup (VDA238-100) [6], and; b) In-plane plane-strain. Tension specimens after fracture

**Figure 2.** Major true strain at fracture measurements in plane strain, conducted using VDA bending and inplane notched coupons for DP980 steel. Source: Butcher and Dykeman [2].

The experimental results shown in Figure 2 indicate approximately ~60-65% increase in strain at fracture obtained using a VDA bending specimen compared to the in-plane notched specimen. This trend is consistent between different sheet thicknesses and materials (with specifics dependent on the material). It is important to note that in both bending and in-plane membrane loading cases (represented by blue and red bars respectively) the fracture strains were measured using DIC. The ‘thinning correction’ (represented by the green bars) was applied by measuring thickness reduction inside the neck of a fractured notched specimen (as opposed to using DIC). While the thinning correction certainly brings the bending and in-plane tension results closer, the difference is still quite significant and the causes are not understood. The trend of increased
ductility in bending (in reference to in-plane tension) has also been observed for other materials (including aluminum) (e.g. Bandpay [1]). This behavior is very consequential not only to material characterization, but also ability to reliably predict fracture in automotive crash and other large scale problems that can only be effectively modeled using shell elements (Voyiadjis and Woelke [8][9], Woelke et al [10]-[12]). In other words, if there are two different tests that produce different values of strain at fracture for nominally the same stress state in a thin sheet of the same material, then which one of these values should be used in the simulation? Since only one input value is possible for each triaxiality level, using critical strain from bending may lead to unconservative results. On the other hand, if in-plane tensile test values are used, the ability of the material to deform without fracture will be severely underestimated (at least in bending). Considering the importance of vehicle efficiency standards and lightweighting efforts, this is a very important problem.

Fundamental understanding of the causes of differences in bending vs. in-plane tensile fracture behavior is necessary to propose a solution. As an initial step, it is useful to examine the details of the fractured tensile and bending specimens shown in Figure 3.

![Figure 3. Plane strain fracture: in-plane tensile fractured specimen and VDA bending fractured specimen (Bandpay [1]).](image)

There are several observations that can be made about the fracture patterns in tension vs. bending. First, fracture of the in-plane tensile specimen seems to have occurred very quickly, i.e. there is no progressive propagation, which is pronounced in bending. In in-plane tension, fracture occurs shortly after shear band develops (at ~45° angle) through the entire thickness of the specimen. More importantly, there is no appreciable necking in bending, while tensile specimen shows significant thinning. This should be reflected in the stress distribution in the specimens, which will be analyzed next.

2. VDA and In-Plane Tension Simulations
A detailed simulation of the VDA bending test is performed to investigate the stress distribution in the sheet. The simulation is not intended to reproduce any specific experimental result, but provide fundamental insight into extensive deformation under bending and compare the result with a corresponding in-plane tension simulation results.

A fine mesh of solid elements with an average element size of 40µm is used to simulate VDA bending of a 1.4mm thick MBW1500 sheet using a Von Mises plasticity model. Fracture is not considered explicitly in this simulation and elasto-plastic response is calibrated based on experimentally measured data following the calibration framework in [4] as shown in Figure 4. The overall model setup and geometry are shown in Figure 5. Symmetry boundary conditions are applied on both front and back surfaces of the model to ensure plane strain condition. Velocity boundary condition is applied to the punch. A detailed view of the deformed shape of the center...
region of the sheet, with contour plots of the through-thickness normal stresses is shown in Figure 6. We note a characteristic flattening of the bottom of the sheet in the center, which is consistent with experimental observations (Figure 3 [1]).

![Stress-strain curve for MBW1500](image1)

**Figure 4.** Stress-strain curve for MBW1500: experimental data and calibration of elasto-plastic material model using VistaCal [4].

![Finite element model](image2)

**Figure 5.** A detailed finite element model of VDA bending of a 1.4mm thick MBW1500 sheet.
The analysis indicates that the through-thickness normal stress is negligible at the bottom of the sheet, where fracture is expected to initiate, while notable compressive develops at the top of the sheet. Compressive stress is not relevant to the overall bending behavior as it is caused by the punch-sheet contact. This suggests that the critical section (i.e. where fracture initiates) remains in a plane-stress state throughout the deformation process. Thus, there is no necking in bending, which is consistent with experimental observations shown in Figure 3. These findings are also consistent with those presented by Roth and Mohr [3].

An analogous simulation is performed for the plane strain in-plane tensile test, as shown in Figure 7. The modeling assumptions and overall attributes (material models, element size) are the same as in the case of bending analysis discussed above.

Initial simulation results confirm that significant through-thickness normal stress develops in the center of the notched in-plane tensile specimen. This results in a much higher level of stress triaxiality, comparing to the bending case, which remains essentially in the plane stress state with 0. This difference in the triaxiality levels explains the differences in the fracture strains measured using both tests.
The difference in stress state under bending and tension is clearly a function of the through-thickness effects, which would be well represented if a relatively fine mesh of solid elements were used to simulate the response (>10 elements through the thickness). However, this resolution is prohibitive for large-scale vehicular impact simulations. Shell elements, on the other hand, are not capable of resolving through thickness effects within the localized zone of deformation (owing to plane stress assumption, i.e. $0$) and they cannot recognize the difference in local stress state in bending vs. tension. With appropriate constitutive model, calibration methodology and modeling approach, the existing layered shell element models can be effective in predicting ductile fracture in either bending or tension, but not both in the same time. This poses a significant challenge to crash modeling community since both in-plane tensile and bending fracture modes can occur in a crash scenario. This challenge can be overcome by either modifying the existing constitutive models (e.g. GISSMO) such that the difference between damage accumulation rate in tension vs. bending is accounted for, or using a non-layered shell formulation. In both cases, a split of the strain tensor into membrane and bending terms is required.

3. Conclusions

Extensive experimental evidence shows a consistent trend of increased strain at fracture of thin metallic sheets in plane strain bending, comparing to plane strain tension (in-plane). The analyses discussed here show that this behavior is directly related to through-thickness normal stress within the localized zone of deformation. In bending, the through-thickness normal stress is essentially negligible while high through-thickness normal stress is developed in plane strain tension (under in-plane loads), within the localized zone of deformation. This leads to significant differences in stress triaxiality for the two considered cases, which gives rise to differences in measured strain at fracture.

Since the underlying causes of the bending vs. tension discrepancy in measured strain at fracture are related to through thickness effects, they cannot be accurately represented under plane stress assumption. This means that current shell element formulations (inherently under plane stress state, i.e. $0$), cannot directly recognize the difference in local stress state in bending vs. in-plane tension. This challenge can be overcome by allowing bending damage accumulation to be treated separately from tension damage. This can be accomplished on the level of a constitutive model, or by means of a non-layered shell formulation, which inherently treats membrane strains and curvatures separately. These modifications are currently being introduced into the VistaDam model [10].

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