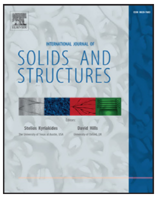
International Journal of Solids and Structures 87 (2016) 254–266

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr



Effect of nonlinear multi-axial elasticity and anisotropic plasticity on quasi-static dent properties of automotive steel sheets

Jeong-Yeon Lee[a,b], Myoung-Gyu Lee[a,b,*], Frédéric Barlat[b,c], Kyung-Hwan Chung[d], Dong-Jin Kim[d]

[a] *Department of Materials Science and Engineering, Korea University, Seoul 02841, Republic of Korea*
[b] *Graduate Institute of Ferrous Technology (GIFT), POSTECH, Pohang, Gyeongbuk 37673, Republic of Korea*
[c] *Center for Mechanical Technology and Automation, Department of Mechanical Engineering, University of Aveiro, 3810-193, Portugal*
[d] *Product Application Center, POSCO, Incheon 21985, Republic of Korea*

ARTICLE INFO

Article history:
Received 16 November 2015
Revised 15 January 2016
Available online 3 March 2016

Keywords:
Dent resistance
Plastic anisotropy
Bauschinger effect
Elastic degradation
Elastic anisotropy

ABSTRACT

This study investigates the influence of the elasto-plastic properties of automotive steel sheets on the denting behavior and suggests a constitutive modeling approach for reliable dent analysis. The stress–strain behaviors of three kinds of steel sheets were measured in uniaxial tension, in-plane biaxial tension and forward-reverse simple shear tests. Advanced constitutive models were employed to capture the plastic anisotropy, reverse loading characteristics such as the Bauschinger effect, and elastic modulus degradation. In particular, the biaxial elastic modulus and its degradation behavior were measured and implemented in the constitutive model. The suggested model significantly improved the prediction of dents compared to the conventional model in terms of the load-displacement curve. Sensitivity studies on the constitutive model demonstrated that mainly plastic anisotropy and elastic behavior of a material influence the panel stiffness, whereas the reverse loading behavior strongly affects the permanent dent depth.

1. Introduction

Panel stiffness and dent resistance are two important quality criteria for automotive outer panels. These properties indicate the ability of a panel to withstand denting under the application of an external load. Automotive denting occurs frequently during the lifetime of a vehicle, including incidents such as hail damage and door-to-door impact, but it is also a concern in the handling of parts during manufacturing. The accurate assessment of panel stiffness and dent resistance is necessary to ensure the robustness of a formed panel throughout the lifetime of the component.

These properties depend strongly on the mechanical properties of the sheet, the deformation paths undergone during forming, panel geometry, and the supporting and external loading conditions. Therefore, with newly designed panel shapes or substitute materials, the stiffness and dent properties must be examined again. This is particularly important considering the current replacement of conventional mild steels by high strength steels (HSS) or advanced high strength steels (AHSS) with reduced thickness for lightweight vehicles.

The direct measurement of dent properties is expensive in cost and time, because a complete toolset is required to form each trial shape. For this reason, a number of empirical relationships have been suggested to correlate dent resistance to the influencing factors. Usually, the static dent energy or dent load has been expressed as a function of elastic properties, yield strength, panel thickness and geometric factors (Dicello and George, 1974; van Veldhuizen et al., 1995). However, these simple expressions are only valid for limited cases, because they ignore the coupling effect among the influencing factors. One example of the coupling effects is that the change of panel curvature affects the amount of plastic deformation applied to the sheet, altering both the yield strength and panel thickness. Moreover, the effects of complex geometry and supporting condition of a real automotive part cannot be sufficiently represented by the few parameters appearing in the proposed empirical relationships. Consequently, these empirical equations are unsuitable to quantitatively assess the dent properties of a panel.

---

[*] Corresponding author at: Department of Materials Science and Engineering, Korea University, Seoul 02841, Republic of Korea. Tel.: +82 2 3290 3269.
E-mail addresses: myounglee@korea.ac.kr (M.-G. Lee), f.barlat@postech.ac.kr (F. Barlat).

http://dx.doi.org/10.1016/j.ijsolstr.2016.01.020

Finite element (FE) analysis allows a realistic modeling of forming and denting procedures, enabling a more reliable assessment of dent properties. However, a proper constitutive description of the sheet is necessary for accurate simulations. First, the plastic anisotropy of the sheet should be described, because automotive outer panels are generally formed under biaxial stress conditions. For this reason, the quadratic anisotropic Hill yield criterion (Hill, 1948) has been used for dent simulations (Holmberg and Nejabat, 2004; Shen et al., 2010). Second, the reverse hardening behavior, such as the Bauschinger effect, needs to be considered, because the sheet may experience reverse loading when a dent occurs on a curved panel. FE simulations using the Chaboche nonlinear kinematic hardening model (Chaboche, 1986) revealed that the description of the Bauschinger effect significantly influenced dent predictions (Shen et al., 2010).

The elastic properties of the sheet are also an important factor because elastic deformation dominates the denting process. When a dent load of 200 N is applied to a dome-stretched steel panel, the permanent dent depth is only 0.2 mm, whereas the maximum deflection of the panel is 7.7 mm (SAE, 2004). This suggests that nearly 97% of the total deflection is elastically recovered when the load is removed. Previous dent studies have assumed a constant value of Young's modulus measured in uniaxial tension tests, usually in the rolling direction (RD) of the sheet. However, experiments on steel sheets have revealed elastic anisotropy and the reduction of the apparent elastic modulus or so-called chord modulus with accumulated plastic deformation (Eggertsen et al., 2011; Sun and Wagoner, 2011). The variation in the initial elastic modulus from the rolling to transverse direction of the sheet is usually 5–10% for steels (Eggertsen et al., 2011). The reduction of chord modulus, as a result of plastic deformation, is about 15–25% for steels, and this phenomenon is mainly attributed to the repulsive interactions between piled-up dislocations (Cleveland and Ghosh, 2002). Therefore, it is necessary to investigate the influence of elastic properties on dent prediction and to determine whether the use of the conventional Hooke's law is appropriate in these analyses.

This study aims to understand the deformation mechanisms undergone by the sheet throughout the forming and denting processes and to suggest a constitutive modeling approach for reliable dent analysis. Three kinds of steel sheets were selected for this study: deep drawing quality (DDQ), bake-hardenable (BH340) and dual-phase (DP490) steels, which are used for automotive outer panels. The stress–strain behaviors of the materials were measured under different loading conditions using uniaxial tension, in-plane biaxial tension and forward-reverse simple shear tests. Advanced constitutive models were employed to describe the measured stress–strain responses in terms of plastic anisotropy, reverse loading behavior and elastic modulus degradation. The adopted models are the non-quadratic anisotropic yield function Yld2000-2d (Barlat et al., 2003), the anisotropic hardening model based on distortional hardening, so-called HAH (Barlat et al., 2011), and strain-dependent elasticity models (Yoshida et al., 2002). The suggested constitutive model was verified using the standard dent test applied in the automotive industry (SAE, 2004), in which the geometry, loading and boundary conditions are precisely defined to minimize experimental scattering or prediction errors caused by factors other than the material properties. This study concerns only quasi-static denting, in which the indenter velocity is slow enough to ignore the strain rate effect.

Section 2 presents a preliminary numerical study on the standard dent test and investigates the deformation mechanism of the sheet. Section 3 describes the experimental procedures for the stress–strain measurement and Section 4 reviews the abovementioned constitutive models. Section 5 presents the verification of the suggested model in the standard dent test and the sensitivity analysis on the influence of material properties. Section 6 demonstrates the usefulness of the standard dent test as a verification example for the abovementioned constitutive models. Finally, Section 7 gives the conclusions and suggestions for future work.

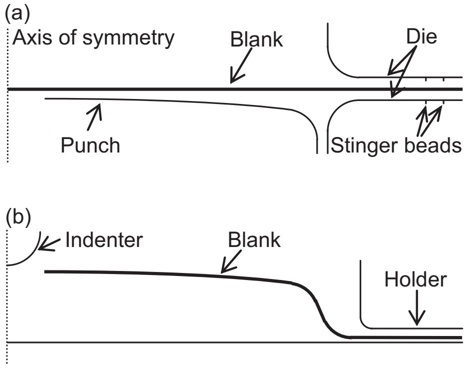


Fig. 1. Schematic for the standard dent test with a dome-stretched panel for (a) pre-stretching and (b) denting. Dimensions are provided in Appendix A.

Table 1
Summary of FE mesh optimization for the standard dent test. Both shell and solid elements are first-order and use reduced integration.

	Shell	Solid
Mesh size in the central region ($r = 50$ mm)	0.1 mm	0.1 mm
Mesh size in the other region	1–3 mm	0.25 mm
Number integration points through thickness	9	–
Number of mesh through thickness	–	7
Relative computation time	1	5.3

2. Preliminary study on the standard dent test

A preliminary FE simulation of the standard dent test (SAE, 2004) was conducted to observe the deformation history of the material through the forming and denting processes. The simulation assumed simple material models, namely, the von Mises yield criterion, isotropic hardening and a constant elastic modulus, using the uniaxial tension data of BH340.

The test procedure consists of two steps, as schematically illustrated in Fig. 1. A 305 mm × 305 mm flat square sheet is formed into a dome-stretched panel with a punch stroke of 12 mm, which results in about 2% biaxial strain prior to denting. Next, the panel is fixed by a holder, subjected to denting using a spherical indenter of 25.4 mm diameter, and unloaded. The tool geometry is described in detail in Appendix A. The standard procedure recommends an incremental increase of the dent load with successive loading-unloading cycles but, for simplicity, only a single loading of 200 N is considered in this study.

A FE model for the dent test was constructed in Abaqus/Standard (implicit) version 6.12. One-quarter of the whole geometry was considered. The tools were modeled using analytical rigid surfaces. Different mesh sizes were assigned in two regions of the sheet: the central region with a radius of 50.8 mm (twice the radius of the indenter) required a fine mesh because the dent was localized in this region, but a relatively coarse mesh was used for the rest. The mesh option was optimized for both shell and solid elements through a series of convergence tests, as summarized in Table 1. The solid and shell elements yielded similar simulation results in terms of the dent profile as well as the load-displacement response of the indenter. This is because the plane stress state dominates during both the forming and denting processes, allowing the stress in the thickness direction to be safely ignored. (It is worth noting that this distinguishes the