A new specimen for out-of-plane shear strength of advanced high strength steel sheets

B Gu¹,², J He¹,², S H Li¹,², Y X Zhao¹,², Y F Li¹,², D Zeng³, Z C Xia³ and Z Q Lin¹,²
¹ State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, Shanghai 200240, China
² Shanghai Key Laboratory of Digital Manufacture for Thin-walled Structures, Shanghai Jiao Tong University, Shanghai 200240, China
³ Ford Motor Company, Dearborn, MI, USA

E-mail: benbenhj@sjtu.edu.cn

Abstract. Compared with the conventional steels, “shear fracture” is one of the main issues for advanced high strength steels (AHSS). Due to rolling, anisotropy is an intrinsic property for sheet metals. Not only the plastic responses of sheet metals but also the fracture strengths are orientation dependent. In the small radius forming process, for example, the stretch-bending deformation of sheet metals under small radius condition, the normal stress cannot be neglected. Three-dimensional loading condition constructs complex shear stress states of sheet metals especially the out-of-plane shear stress. The out-of-plane performance must be considered in order to better understand the “shear fracture” phenomenon of AHSS. Compared to in-plane shear test, the out-of-plane shear test is more difficult to carry out due to the severe restriction of the dimensions in the thickness direction. In this paper, a new specimen is presented for out-of-plane shear test. Failure of the specimen occurs in shear between two centrally located notches machined halfway through its thickness from opposing sides. Meanwhile, the finite element (FE) model and possible failure modes of this specimen are investigated in detail. At last, brief experimental results between out-of-plane shear fracture strength and the in-plane shear fracture strength are compared for DP980 sheets.

1. Introduction
In the past decade, advanced high strength steels (AHSS) have been widely used instead of the conventional mild and high strength steels in the automobile industry for weight reduction and safety performance improvement. Compared with the conventional steels, AHSS are relatively brittle and vulnerable to fracture during forming processes. One typical problem is the “shear fracture” phenomenon occurring on the stretch-bending deformation of sheet metals under small radius condition [1-8]. This type of fracture occurs parallel to and near the die radius, exhibits little localized necking and presents 45° slant crack through thickness. The shear fracture strain is usually below the conventional Forming Limit Diagram (FLD) of the material and traditional necking theory is unable to describe this type of fracture.
Generally, the fracture behavior of sheet metals depends on the loading direction. In the small radius forming processes, the normal stress cannot be neglected. Three-dimensional loading condition constructs complex shear stress states for sheet metal especially the out-of-plane shear stress. Besides, sheet metals, which have undergone extensive plastic deformation due to the continuous rolling process, exhibit a significant anisotropy of mechanical properties. Not only the plastic responses of sheet metals are anisotropic, but also the fracture strengths are orientation dependent. For AHSS, martensitic islands are likely to form and congregate in the middle of the sheet layer. As a result, the sheet metal is weaker under out-of-plane shear loading than in-plane shear. It is necessary to consider the out-of-plane properties of sheet metals in order to better understand and predict the “shear fracture” phenomenon of AHSS.

The out-of-plane experiments are particularly needed for a better understanding of out-of-plane performances of AHSS. Such works have received little attentions in previous investigations due to the severe restriction of the dimensions in the thickness direction for sheet metals. This is relatively easier for thick plates, when thickness is over 20 mm. To investigate the anisotropic ductile fracture of Al 2024 alloys, Steglich et al. [9] carried out a series of tensile tests loading in the L (longitudinal), T (transverse) and S (short-transverse) directions by using the smooth round bar specimens and the notched round bar specimens with different notch radii, which were extracted from a hot-rolled plate of Al 2024 with a thickness of 100 mm. To modeling the anisotropic hardening behavior for the fracture prediction of 22 mm thick high strength steel line pipes, Iob et al. [10] designed a 17 mm long mini round tensile specimen, which was extracted in the through thickness direction of the pipe. However, for sheet metals, which are widely used in the car body, the thickness is usually less than 3 mm. It is difficult to realize the out-of-plane tensile test even with the mini round tensile specimen mentioned above. Therefore, the fracture experiments for sheet metals are mainly restricted to the in-plane tests at present, like in-plane tensile tests on classical dog-bone specimens, flat specimens with cutouts, plane strain grooved specimens, in-plane shear tests, in-plane shear/tension tests on butterfly specimens and so on [11-13]. The out-of-plane properties of sheet metals obtained from these in-plane tests are only approximate or even incorrect sometimes. It is significantly important and necessary to design new out-of-plane specimens and set up relevant out-of-plane tests for sheet metals.

In this paper, the initial idea of a new specimen for out-of-plane shear strength of sheet metals and its challenges are presented at first in Section 2. Then in Section 3, the finite element (FE) model and possible failure modes of this specimen are investigated in detail. The brief experimental results between out-of-plane shear fracture strength and the in-plane shear fracture strength are compared in Section 4 followed by a summary of conclusions in Section 5.

2. New out-of-plane double notched shear specimen

The schematic diagrams of the in-plane shear specimens and the out-of-plane shear specimens are exhibited in figure 1. For simplicity, the three principal material directions of sheet metal are defined as the rolling direction (RD), transverse direction (TD) and normal direction (ND). The two-letter code is used in figure 1 to describe the specimen orientations and loading directions [14]. The first letter designates the normal to the expected shear plane or the fracture plane. The second letter designates the direction of load application or the expected fracture direction. The most commonly used specimen orientation and loading direction is T-R or R-T for in-plane shear. Compared to the in-plane shear test, the out-of-plane shear test (N-R or N-T) is more difficult to carry out due to the severe restriction of the dimensions in the thickness for sheet metals.

The initial idea of the new specimen for out-of-plane shear strength of sheet metals was proposed by Li et al. [15]. The schematic diagram of the novel out-of-plane double notch shear specimen (DNS-Specimen) is presented in figure 2. A rectangular strip with the length of \( L_0 \) and width of \( W_0 \) is extracted from a sheet metal with the thickness of \( t_0 \) at first. Then two parallel and centrally located notches, one on each opposite side and across the entire width of the specimen, are machined halfway through its thickness and spaced a fixed distance \( L_j \) apart along the length of the specimen. Failure of the DNS-Specimen will occur in shear between the two notches when applying a tensile load.
Great challenges exist when carrying out the out-of-plane shear test with the DNS-Specimen. Since the thickness of the AHSS sheet is usually less than 3 mm and the actual dimensions of the notches will greatly influence the performance of the NDS-Specimen, it is the first challenge to machine the notches from the thickness direction and guarantee their dimensional precisions. Secondly, the shear zone of the DNS-Specimen is such tiny (about 0.5 mm × 1.0 mm) that traditional speckle spraying method and digital image correlation (DIC) equipment are not applicable for the deformation measurements. The DIC equipment with higher resolution and the method to create much finer speckle pattern are required. The last but not least, the shear zone will rotate easily due to the asymmetry of the specimen without the external transverse restriction, an anti-rotating clamping device must be carefully designed.

**Figure 1.** The schematic diagrams of specimen orientations and loading directions.

**Figure 2.** The schematic diagram of the new out-of-plane DNS-Specimen.
3. Possible failure modes for the DNS-Specimen

Finite element (FE) simulation has been performed for the out-of-plane shear test to analyze the possible failure modes for the DNS-Specimen. For the simulation, 1.0 mm thick dual-phase steel sheet of 980 MPa ultimate tensile strength (DP980) is assigned to the models. All the FE simulations are executed in the environment of ABAQUS Standard using the von Mises yield criterion. The Swift hardening rule given by equation (1) is adopt, with \( A=1437 \text{ MPa}, n=0.086 \) and \( \varepsilon_0=0.00051 \),

\[
\bar{\sigma} = A(\varepsilon^p + \varepsilon_0)^n
\]

where \( \bar{\sigma} \) is equivalent stress, \( \varepsilon^p \) is plastic strain, and \( A, \varepsilon_0 \) and \( n \) are material parameters.

The detailed mesh and boundary conditions of the three-dimensional (3D) finite element model for the DNS-Specimen is presented in figure 3. The models are carefully meshed using reduced-integration eight-node solid elements (type C3D8R). The global element size is set to 0.20 mm while in the shear zone elements with a size of 0.025 mm are used. The size of the remaining elements is adapted automatically to avoid any deformations of the mesh. The anti-rotating clamping plates are modeled as a rigid wall contact on either side of the specimen. The Coulomb friction coefficient between clamping plates and the specimen was assumed to be zero. Loading is applied via a prescribed displacement at one end of the specimen while the nodes at the other end are fixed.

![3D model](image.jpg)

**Figure 3.** The finite element model of the DNS-Specimen.

When applying a tensile load, there will be three possible failure modes for the DNS-Specimen: (a) rotation of the shear zone, (b) shear fracture of the shear zone and (c) necking of the arm, as shown in figure 4. On one hand, without external transverse restriction, the shear zone will rotate easily due to the asymmetry of the specimen (red arrows in figure 4(a)). It can be found that the rotation could be effectively suppressed by an anti-rotating clamping device from figure 4(b). On the other hand, there exists a competition between shear fracture of the shear zone and necking of the arm (figure 4(b)-(c)). To ensure failure by shear, the tensile stresses at the arms can’t exceed the material strength \( \bar{\sigma} \). This requirement relates the \( L/l_0 \) ratio to the shear strength \( \dot{\tau} \) and normal strength \( \bar{\sigma} \) through

\[
\frac{L_1}{l_0} \leq \frac{1}{2} \frac{\bar{\sigma}}{\dot{\tau}}
\]
Failure by shear is prior to the necking of the arm for the DNS-Specimen when the $L_1/t_0$ ratio is 0.5 (red arrows in figure 4(b)). On the contrary, necking of the arm will dominate the failure at last when the $L_1/t_0$ ratio is equal to 1.0 (red arrows in figure 4(c)). Therefore, the $L_1/t_0$ ratio equal to 0.5 is chosen in the following study.

![Diagram](image)

**Figure 4.** Three possible failure modes for the DNS-Specimen: (a) rotation of the shear zone, (b) shear fracture of the shear zone and (c) necking of the arm.

4. **Comparison of the out-of-plane and in-plane shear fracture strengths**

The out-of-plane shear tests are performed on an Instron 10 kN universal testing machine under displacement control at a constant crosshead velocity of 0.50 mm/min. The detailed setup of the experiment could refer to the work done by Li et al. [15]. To compare with the out-of-plane shear test, the modified ASTM specimen (as shown in figure 5) proposed by Merklein and Biasutti [16] is adopted for in-plane shear test. The in-plane shear specimens are extracted along the rolling direction (RD) and the transverse direction (TD) by wire cut electrical discharge machining (WEDM). Each test with different specimen orientation and loading direction will repeat three times during the whole experimental procedure.

The shear fracture strength $\tau^f$ for the out-of-plane shear and the in-plane shear can be calculated as follows [14]:

$$\tau^f = \frac{F_{\text{max}}}{A_0}$$

(3)

where $F_{\text{max}}$ is the maximum force during the test, $A_0$ is the initial area of the shear zone. For the out-of-plane DNS-Specimen, $A_0$ equals to the initial length of the shear zone ($L_1$) multiplied by the initial width of the specimen ($W_0$). For the modified ASTM specimen, $A_0$ equals to the initial length of the shear zone multiplied by the initial thickness of the specimen ($t_0$).
Figure 5. The dimension of the modified ASTM specimen.

The comparison of the fracture strengths of the out-of-plane shear tests and the in-plane shear tests is presented in figure 6. For in-plane shear test, the shear fracture strengths along the rolling direction (RD) and the transverse direction (TD) are almost the same and so it is with the out-of-plane shear fracture strengths in the rolling direction (RD) and the transverse direction (TD). However, compared with the in-plane shear fracture strength, the out-of-plane shear fracture strength is near 80 MPa lower. We briefly give the possible reason for such phenomenon as follows: The DP steel sheets will form particular martensitic island structure geometry and distribution during the continuous rolling process. From a microscopic point of view, the primary micro-voids or cracks present a preferential direction according to the geometry of inclusion. For DP steel sheets, martensitic islands are likely to form and congregate in the middle of the sheet layer and micro-voids are likely to nucleate at the interfaces of these hard and brittle martensitic islands. As a result, the sheet metal would be weaker when the shear plane is perpendicular to the thickness direction. The difference between the out-of-plane and in-plane shear fracture strengths may greatly influence the failure behavior of sheet metals when the out-of-plane loading is dominant, for example, during the stretch-bending deformation of sheet metals under small radius condition. The detailed research about the microstructural features and “shear fracture” phenomenon of AHSS under this framework is worth further investigating.
5. Conclusion
The main purpose of this work is to present an out-of-plane shear test for AHSS sheets and to compare the out-of-plane shear fracture strength with the in-plane shear fracture strength. Based on the above study, the following conclusions can be made:

(1) A new out-of-plane double notched shear specimen (DNS-Specimen) is presented.
(2) When applying a tensile load, there will be three possible failure modes for the DNS-Specimen: (a) rotation of the shear zone, (b) shear fracture of the shear zone and (c) necking of the arm.
(3) For the DNS-Specimen, the ratio of the length of shear zone to the thickness of the specimen is the critical parameter to determine whether failure by shear is prior to the necking of the arm or not.
(4) For DP980 sheets, the out-of-plane shear fracture strength is lower than the in-plane shear fracture strength.

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