Issues associated with the use of Yoshida nonlinear isotropic/kinematic hardening material model in Advanced High Strength Steels

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Abstract. The Yoshida nonlinear isotropic/kinematic hardening material model is often selected in forming simulations where an accurate springback prediction is required. Many successful application cases in the industrial scale automotive components using advanced high strength steels (AHSS) have been reported to give better springback predictions. Several issues have been raised recently in the use of the model for higher strength AHSS including the use of two C vs. one C material parameters in the Armstrong and Frederick model (AF model), the original Yoshida model vs. Original Yoshida model with modified hardening law, and constant Young's Modulus vs. decayed Young's Modulus as a function of plastic strain. In this paper, an industrial scale automotive component using 980 MPa strength materials is selected to study the effect of two C and one C material parameters in the AF model on both forming and springback prediction using the Yoshida model with and without the modified hardening law. The effect of decayed Young's Modulus on the springback prediction for AHSS is also evaluated. In addition, the limitations of the material parameters determined from tension and compression tests without multiple cycle tests are also discussed for components undergoing several bending and unbending deformations.

1.0 Introduction

Advanced high strength steels (AHSS) are widely used in automotive body-in-white (BIW) components due to their potential weight-saving properties, while maintaining component performance in crashworthiness and structural durability. The application of AHSS in a typical vehicle will be increased from an average of 254 lbs in 2014 to an average of 483 lbs by 2025 based on a forecast by Ducker [1]. The driving force behind this forecast is the ever-increasing innovations in new steel development. Gen-3 steels aim to achieve a balance between press hardening steels (PHS) and Gen-1 dual phase steels by having higher elongation than PHS and higher strength than dual phase steels. The advantage of having higher elongation is that it is possible to cold stamp those steels using conventional stamping presses, thereby reducing fabrication cost. An additional promising feature of Gen-3 steel is its high fracture resistance compared to PHS, which makes the usage of Gen-3 steels in body-in-white (BIW) structure components attractive. Nevertheless, research has shown that for BIW applications, steels with yield strengths higher than 1.3 GPa are required for significant weight savings. However, one of the significant challenges during cold forming those steels is springback control. The ability to accurately predict springback after forming and trimming is essential in

minimizing the number of die re-cuts and developing compensated dies with minimal springback and springback variation. Typically, AHSS including those Gen-3 AHSS show a significant Bauschinger effect during reverse loading and a nonlinear combined isotropic and kinematic hardening law is required to capture the Bauschinger effect of those materials. The use of the nonlinear isotropic/kinematic hardening material model proposed by Yoshida, et al [2] is useful in forming simulations where an accurate springback prediction is required. For materials such as steels showing continuous strain hardening behaviour, the Yoshida model with a modified hardening law proposed by Shi, et al [3] is often used. Many successful application cases in industrial scale automotive components using advanced high strength steels (AHSS) have been reported to give better springback predictions [4]. Several issues have been raised recently in the use of the model for higher strength AHSS including the use of two C vs. one C material parameters in the Armstrong and Frederick model (AF model), the original Yoshida model vs. Original Yoshida model with modified hardening law, and constant Young's Modulus vs. decayed Young's Modulus as a function of plastic strain. In this paper, the consistency of the material model parameters determined from the tension and compression test is verified using a one-element simulation for a 980 MPa material. Using an industrial scale automotive component, the difference in forming and springback results is addressed for two C and one C material parameters in the AF model using the Yoshida model with and without the modified hardening law. The effect of decayed Young's Modulus on springback prediction for AHSS is also evaluated. In addition, the limitations of the material parameters determined from the tension and compression tests without multiple cycle tests are discussed for those components undergoing several bending and unbending deformations.

2.0 Determinations and verifications of Yoshida model parameters

Two different types of tension and compression tests were carried out: a full cycle test and a multiple cycle test, as shown in Figure 1. The multiple cycle tests were designed to capture material hardening behaviour in loading after the material was subjected to one or more tension and compression cycles. The pure tension data were also included in Figure 1, where the pure tension data coincide with the initial tension portion of the data in the tension and compression tests, as expected.
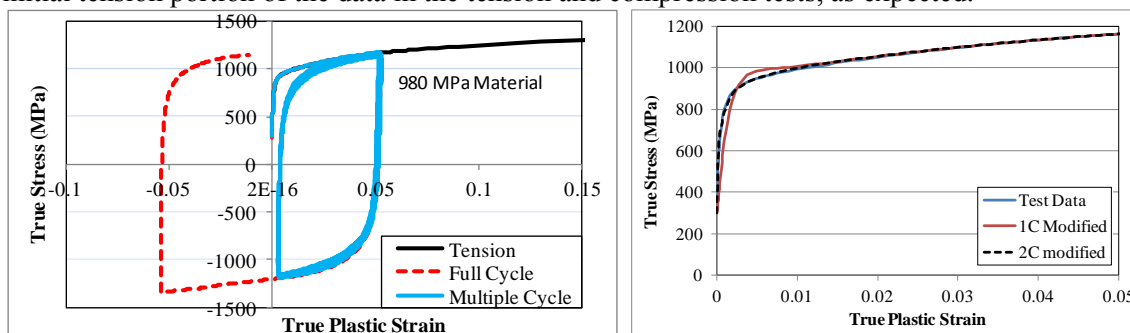

Figure 1 Tension and compression test data and data fitting of one C vs. two C models

Table 1 Material Constitutive Parameters for Original and Modified Yoshida Models

Modified	Symbols in the paper	Y (MPa)	B (MPa)	C	m	b (MPa)	h	K (MPa)	e0	N	C2
980MPa	One C Model	300	844.4	712.2	49.5	330.4	0.95	1527.3	0.010	1.13	
980MPa	Two C Model	300	835.2	657.2	48.0	323.1	0.95	1270.3	0.0535	0.93	1971.5
Original	**Symbols in the paper**	**Y (MPa)**	**B (MPa)**	**C**	**Rsat (MPa)**	**m**	**b (MPa)**	**h**	**C2**		
980MPa	One C Model	300	824.2	660.8	124.8	44.5	317.6	0.95			
980MPa	Two C Model	300	813.2	591.1	157.9	41.5	302.9	0.94	1773.2		

The material constitutive parameters were determined using an optimisation algorithm using the data shown in Figure 1(a), as shown in Table 1 for both original Yoshida model [2] and modified model

[3], where material model parameters for both one C and two C models were provided. The Two C model was selected to describe the initially higher stain hardening behaviour of AHSS. It seems from Figure 1(b) that the 2C model is better able to describe the higher strain hardening at low strain than the one C model.

The one element model was used to verify the effectiveness of the model implementation in LS-DYNA. The tension and compression test was simulated in the one element model using the parameters identified in Table 1. As shown in Figure 2, the predicted stress and strain data are consistent with the tested data from the one-element model for the original Yoshida model and the modified model. As expected, the two C model is able to capture the higher strain hardening behaviour of the material at low strains.
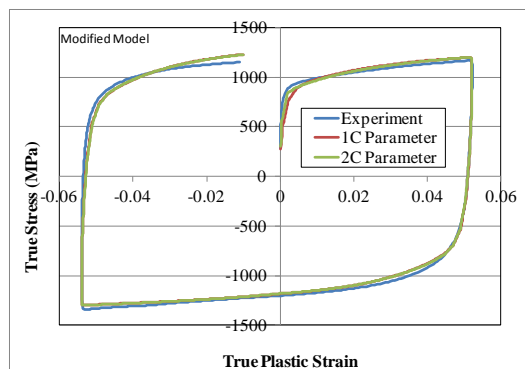

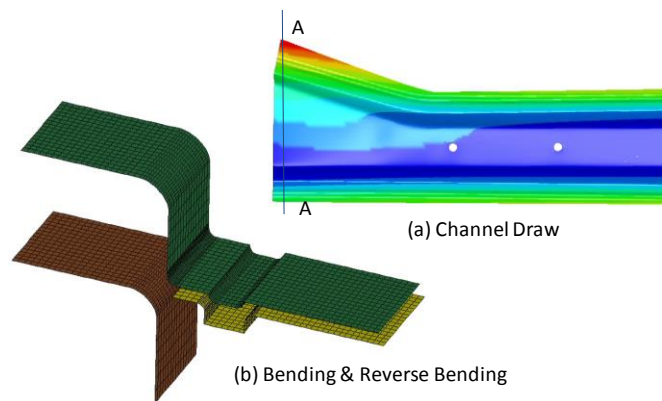Figure 2 One-element Simulation Results   Figure 3 Components used in this study

3.0 Springback and forming strain prediction comparison

A channel draw type of industrial component was selected to evaluate the difference in the springback prediction using various models such as the one C vs. the two C models, the original Yoshida model vs. the modified Yoshida model (continuous hardening), the constant Young's modulus model vs. the decayed Young's Modulus model, as well as the Yoshida model vs. the conventional isotropic material model. As shown in Table 2, the maximum springback predictions along section A-A, including side wall curl, angle change and twist, show very similar results between one C and two C models (about 1% difference). The Yoshida model with the modified hardening law results in higher springback than the original Yoshida model while the conventional isotropic hardening model predicts significantly lower springback. As suggested by Yoshida [2], a decayed Young's Modulus (E) value may be used at various strains using the following equation:

$$E = E_0 - (E_0 - E_1)(1 - e^{-\alpha\varepsilon_p})$$

Where E_0, E_1, and α are constants and ε_p is the plastic strain. In our case where E_0 equal to 205 GPa, E_1 equal to 192 GPa, and α equal to 184, the delayed E predicted higher springback than the constant E, as shown in Table 2. However, the modified model with a constant E predicted a similar springback to the original model with delayed E. The use of a decayed E has no effect on the forming results for both models.

Table 2 Springback and thinning results for the channel and cross member

	Channel Draw					
	One C Modified	Two C Original	Two 2C odified	Isotropic	Two C Modified + Decayed E	Two C Original + Decayed E
Max Thinning (A-A) (%)	8.4	9.0	8.3	8.2	8.3	9.0
Max Thinning (part) (%)	8.7	9.7	8.7	9.4	8.7	9.7
Max Springback (A-A) (mm)	60.8	57.3	60.0	53.9	62.7	60.0

As shown in Table 2, all models predicted very similar thinning for this part and the amount of thinning is below 14% thinning limit for this material.

4.0 Effect of multiple cycle test result on forming and springback prediction
Most publications including the Numisheet 2011 benchmark use only a full cycle of the tension and compression test data to determine the Yoshida model parameters. As pointed out in [3], a multiple cycle of the tension and compression test should be included in the parameter determination, which is particularly important if a part is subject to multiple loadings and reserve loadings. The effect of multiple cycle test data on the overall forming and springback prediction can be demonstrated by a simple bending and reserve bending case, as shown in Figure 3. The modified Yoshida model parameters were also obtained excluding the multiple tension and compression test data in the parameter determination. The predicted maximum thinning and maximum springback in the z direction are respectively 13.6% and 28.0 mm using the parameters determined with all test data and 12.0% and 24.5 mm respectively using the parameters determined with the test data excluding the multiple cycle test. This case study clearly indicates that the multiple cycle test data should be included in the Yoshida model parameter determination, particularly for those parts subject to two or more loading and unloading cycle.

5.0 Conclusions
Based on the above study, the following conclusions can be made:
The two C model can capture the higher straining hardening behaviour of AHSS at a lower strain portion. Both one C and two C model predicted similar thinning but slightly different springback.
The modified Yoshida models predicted slightly higher springback than the original Yoshida model while the isotropic hardening model predicted significantly lower springback than the original and modified Yoshida models.
The use of decayed Young's Modulus resulted in higher springback prediction than the use of the constant Modulus.
The multiple cycle tension and compression test must be used in parameter determination, particularly for those parts subject to two or more loading and unloading deformations.

6.0 Reference
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