# Yoshida-Uemori model: Improvement of the elastic modulus evolutive model and Springback application.

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**Abstract.** Today, a combined hardening model coupled with the elastic evolution modulus which depends on the equivalent plastic strain, called Yoshida-Uemori model, is recommended for an improved springback prediction in stamping numerical simulation. The identification of the elastic evolution modulus parameters is based on hysteresis loops realized between 0.2% of plastic deformation and uniform elongation (UEL), by steps of 1%. The direction change point of each loop is close to 5 MPa. At the equilibrium state of a stamped part after springback, the stress state is not zero at all integration points. Two solutions allow to improve the elastic modulus evolutive model to consider the final stress state in addition to the cumulative plastic deformation. The first solution consists at an implement a full loops model in FEA code; The second solution is to realize two springback steps: the first is a step with constant elastic modulus to obtain the final stress state then defined a model according to this stress state and plastic equivalent strain. To demonstrate the benefits of considering the final stress state in addition to the cumulative plastic deformation, the 2nd solution is applied in the springback prediction of U-form stamping part.

**Keywords:** Yoshida-Uemori; Steel; Sheet; Springback; Stamping; FEA.

## 1 Introduction

The Yoshida-Uemori model [1-3] recommended for an improved springback prediction in stamping numerical simulation [4-7] is a combined hardening model coupled with the elastic evolution modulus which depends on the equivalent plastic strain. Yoshida-Uemori material cards considering the various implementations of this model in the most used stamping softwares PamStamp®, LS-DYNA® and Autoform® has been established by ArcelorMittal for its products. The methodology for identifying the Yoshida-Uemori parameters is based on reversed shear test and hysteresis loops [8-9]. For elastic evolutive modulus model, is the value of the modulus of elasticity consistent with the final state of stress after springback? One solution is applied in the springback prediction of U-form stamping part to demonstrate the benefits.

## 2 Evolutive elastic modulus model of Yoshida-Uemori

The hysteresis loops (Fig. 1) between 0.2% of plastic deformation and uniform elongation (UEL), by steps of 1%, are realized to capture the evolution of elastic modulus with plastic pre-strain. The strain is measured with a high-resolution Zwick® digiClip extensometer as per Annex G of ISO 6892-1 standard [10].

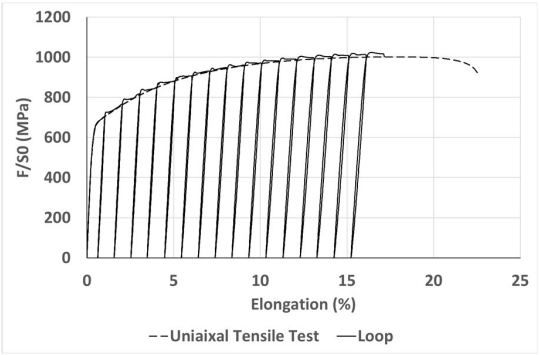


**Fig. 1.** Hysteresis loops (Figure 1) between 0.2% of plastic deformation and uniform elongation (UEL), by steps of 1% for a Fortiform® 980 steel (more details in [11]).

The direction change point of each loop is close to 5 MPa (Fig. 2). The elastic modulus is the slope deducted from the linear regression on unloading path between points A (maximal stress at the begin of the loop) and B (minimal stress of loop). The evolution of the elastic modulus in the Yoshida-Uemori model is equal to:

$$E(p) = E_0 - (E_0 - E_a)\left(1 - exp(-\xi p)\right) \quad (1)$$

where $E_0$ is initial young modulus, p is equivalent plastic strain, $E_a$ and $\xi$ are two adjusting parameters fitted according to a gradient method (curve on Fig. 3) to get the better correspondence between equation (1) and

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experimental results derived from hysteresis loops tests (points on Fig. 3).

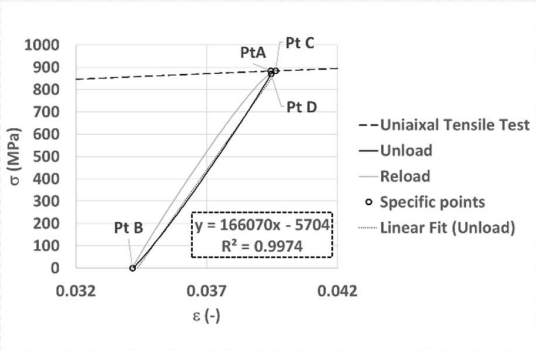


**Fig. 2.** The elastic module deducted from the linear regression on unloading path between the points A and B for a Fortiform® 980 steel.

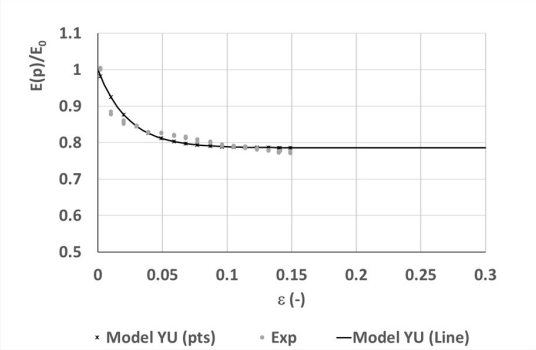


**Fig. 3.** Experimental points versus Elastic modulus evolution model (YU: Yoshida-Uemori) for a Fortiform® 980 steel ($\boldsymbol{E_0}$=210GPa, $\boldsymbol{E_a}$=157GPa and ξ=42.85).

## 3 Final state of stress after springback

The equilibrium state of a stamped part after springback is not zero at all integration points (Fig.4). For a Fortiform® 980 steel, a springback prediction study realized with PamStamp®2022 about 9 stamping parts shows only less than 5% of the integration points are close to zero (Table 1) [9, 12].

**Table 1.** Specific information State of Integration points (Fortiform® 980 steel). (BHF: Blank Holder Force)

| Parts | Integration Points | |
|---|---|---|
| | Number in part | Stress state after Springback close to 0 (± 5 MPa) |
| U-Form (Low BHF) | 388340 | 1.2 % |
| U-Form (High BHF) | 397085 | 0.1 % |
| Inner side-sill part | 272745 | 0.6 % |
| Roof arch reinforcement | 832780 | 0 % |
| Rear side-rail part | 639485 | 2.5 % |
| Door lateral beam | 428940 | 1.1 % |
| A pillar part | 714015 | 4.8 % |
| Floor reinforcement part | 681635 | 2.8 % |
| Front side-rail part | 178725 | 2.8 % |

For a CR450Y780T-TR steel grade (more details in [13]), hysteresis loops are stopped at different levels of stress (Fig. 5). Starting from the same point on the flow curve, larger is the range, lower is the value of the elastic modulus (Table 2). On the same stress range, the modulus value is same whatever the minimum stress at stop of the loop.

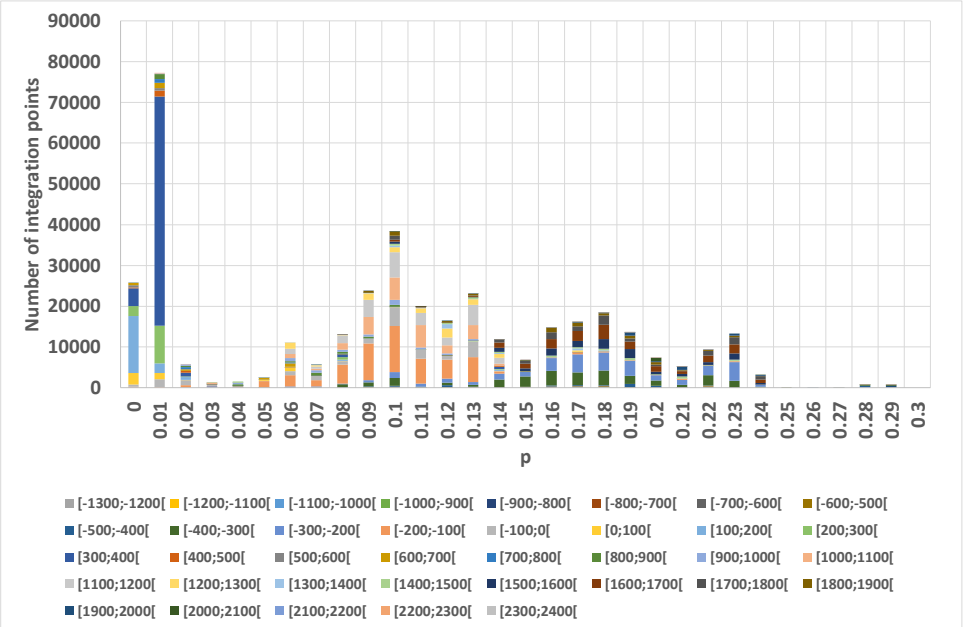


**Fig. 4.** Stress state after springback in U-Form (Low BHF) for Fortiform® 980. The stress ranges indicated in the legend are for the major main stress. (p: Equivalent plastic strain)

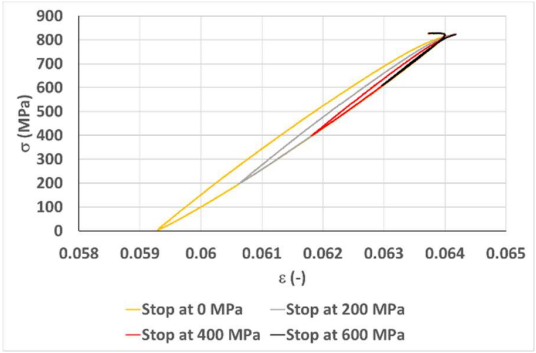


**Fig. 5.** For CR450Y780T-TR steel, Loops at different minimum stresses: 0; 200; 400 and 600 MPa.

**Table 2.** Elastic Modulus (GPa) determined over different stress intervals for a CR450Y780T-TR steel.

| Stress intervals (MPa) | Stop at 0 MPa | Stop at 200 MPa | Stop at 400 MPa | Stop at 600 MPa |
|---|---|---|---|---|
| [800 – 600] | 214 | 214 | 214 | 212 |
| [800 – 400] | 195 | 196 | 195 | |
| [800 – 200] | 184 | 186 | | |
| [800 – 0] | 173 | | | |

## 4 Improvement of the elastic modulus evolutive model

Ideally, a model that correctly predicts the hysteresis loop (full loop model) (Fig.6) should be implemented to obtain an elastic modulus that depends on the final stress state.

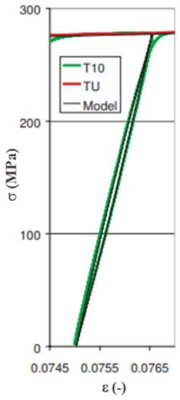


**Fig. 6.** Comparison an experimental loop and the prediction of full loop model proposed by [14].

The full loop model proposed by [14] is based on decomposition reversible compliance ($C_{REV}$) additively into a classical elastic compliance ($C_{ELA}$) and a stress-dependent anelastic compliance ($C_{ANE}$):

$$C_{REV} = C_{ELA} + C_{ANE} \quad (2)$$

Four fundamental facts deduced from experimental observation on hysteresis loop are:

- After plastic strain, the apparent elastic modulus is lower than the theorical Young's modulus.
- During the unloading of a tensile specimen, the instantaneous elastic modulus decreases with the decreasing stress and three stages can be observed. In the first stage, it starts from a value close to the theorical Young's modulus and decreases rapidly. In the second stage, it decreases more or less linearly. It decreases rapidly in the third stage.
- During the reloading of pre-strained tensile specimen, the same three stages seem to appear as the reloading stress increases.
- The anelastic effects are reversible.

The full loop model proposed by [14] reproduces the three observed stages with an analytical form of the anelastic curve $\chi = function(\mu)$ governed by means of two controlled points delineating the three anelastic stages (Fig. 7). $\chi = C_{ANE}/C_{ELA}$ is the anelastic compliance normalized and $\mu = |\sigma_{EQ} - \sigma_{EQ,REV}|/(2\sigma_{FLOW})$ is the normalized stress measurement with $\sigma_{EQ}$ the current equivalent stress, $\sigma_{EQ,REV}$ the floating equivalent stress and $\sigma_{FLOW}$ the flow stress. Five material parameters are needed to fix the shape of the anelastic curve (Table 3).

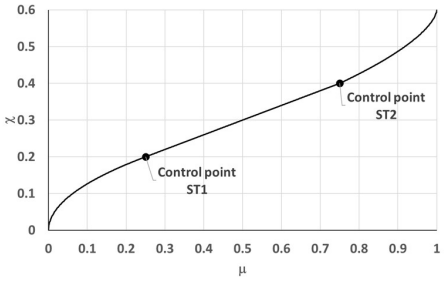


**Fig. 7.** Curve of normalized compliance used as input for the full loop model proposed by [14].

**Table 3.** Five material parameters of full loop model.

| Material parameters | Definition |
|---|---|
| $\mu_{ST1}$ | Abscissa of the first control point |
| $\chi_{ST1}$ | Ordinate of the first control point |
| $\mu_{ST2}$ | Abscissa of the second control point |
| $\chi_{ST2}$ | Ordinate of the second control point |
| $\chi_{MAX}$ | The maximal value of the normalized anelastic compliance |

The shape of the anelastic curve is modelled by means of a piecewise analytical definition, which involves five coefficients that can be calculated as soon as the two control points and the value of $\chi_{MAX}$ have been defined:

$$\begin{gathered} \text{if } \mu \in [0, \mu_{ST1}[ \text{ then } \chi = K_{ST}\ \mu^{NS} \\ \text{if } \mu \in [\mu_{ST1}, \mu_{ST2}] \text{ then } \chi = \chi_{ST1} + K_{ST2}(\mu - \mu_{ST1}) \\ \text{if } \mu \in ]\mu_{ST2}, 1] \text{ then } \chi = \chi_{MAX} - K_{ST3}(1-\mu)^{NST3} \end{gathered} \quad (3)$$

with

$$\begin{gathered} K_{ST2} = (\chi_{ST2} - \chi_{ST1})/(\mu_{ST2} - \mu_{ST1}) \\ NST1 = K_{ST}\ \mu_{ST1}/\chi_{ST1} \\ K_{ST1} = \chi_{ST1}/{\mu_{ST1}}^{NST} \\ NST3 = K_{ST2}(1-\mu_{ST2})/(\chi_{MAX} - \chi_{ST2}) \\ K_{ST}\ = (\chi_{MAX} - \chi_{ST2})/(1-\mu_{ST}\ )^{NST3} \end{gathered} \quad (4)$$

Before to implement a full loop model in FEA Code, to check the interest of an elastic modulus model to consider the stress state after springback, a linear elastic model with a 2-steps springback is only used:

- Step 1: simulation with a constant elastic modulus of 210 GPa to obtain the internal stress state after springback.
- Step 2: simulation with elastic modulus according to the equivalent strain before springback and the final stress state of the first step.

To achieve step 2, the equation 1 of Yoshida-Uemori has been modified to:

$$E(p) = E_0 - (E_0 - E_a)\left(1 - exp(-\xi p^n \Delta\sigma^q)\right) \quad (5)$$

where n and q are two additional material parameters, $\Delta\sigma$ is the difference equivalent stress before and after springback. It is the same definition proposed in [10] but normalized. As for equation (1), the parameters are approximated by a gradient method to get the better correspondence between equation (5) and experimental points (Fig. 8).

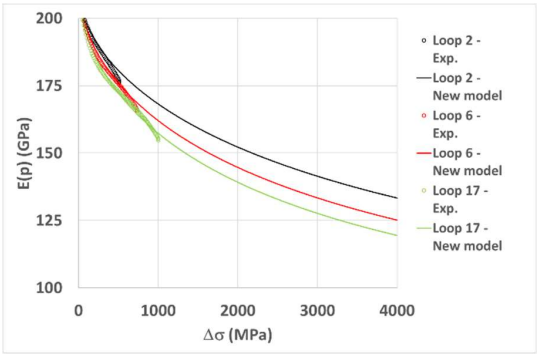


**Fig. 8.** Comparison between new model and experimental points for Fortiform® 980 steel ($\boldsymbol{E_0}$=210GPa, $\boldsymbol{E_a}$=76.3GPa, n=0.108, q=0.601 and $\xi$=0.01).

## 5 Springback application

To demonstrate the benefits or not to consider the stress state after springback, the solution "linear elastic model with a 2-steps springback" is applied to predict the springback of U-form stamping (Low BHF) for Fortiform®980 of thickness = 1.2 mm.

The stamping step is realized with explicit Abaqus®2021. The blank elements used are shell elements S4R with 5 Gauss points. The element size is 1x1 mm² allowing more than 5 elements in the radius of the punch or die. Unlike previous publications [9, 12] where PamStamp®2022 FEA code was used, it was not possible to use Yoshida-Uemori's hardening law in Abaqus®2021. An isotropic hardening law (exp_S, more details in [15]) was therefore used.

For the springback step, an isotropic elastic linear user routine (umat) of Standard Abaqus®2021 is used for four cases: two constant elastic moduli (210 and 150 GPa); Yoshida-Uemori model (eq.1) and Yoshida-Uemori modified model (eq.5).

Figure 9 shows a different distribution of the elastic modulus for springback between the 2 models in terms of the number of Gauss points. However, the planar distribution of this elastic modulus remains almost identical (Fig. 10).

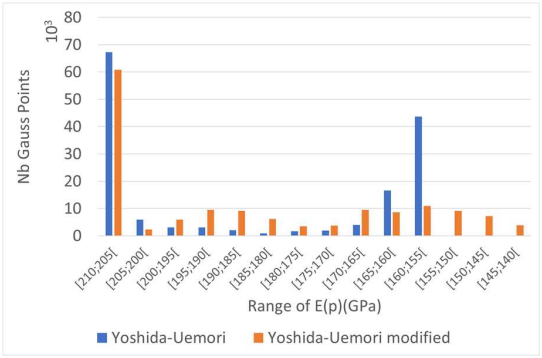


**Fig. 9.** Nb Gauss of Range of elastic modulus.

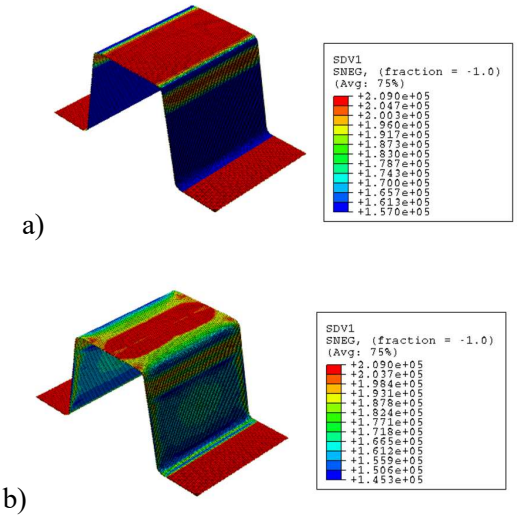


**Fig. 10.** Elastic modulus distributions before springback: a) Yoshida-Uemori law; b) Yoshida-Uemori modified. (SDV1=Elastic Modulus in MPa)

Despite different modulus of elasticity distributions, the 2 models predict the same profile positioned between the 2 constant value cases (Fig. 11).

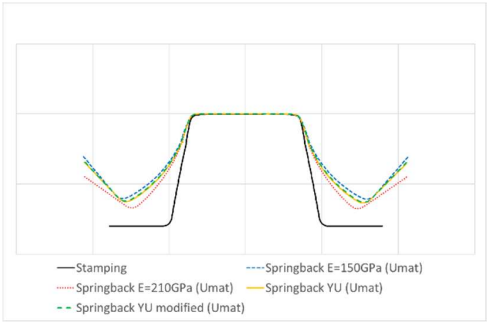


**Fig. 11.** Profile after springback (YU: Yoshida-Uemori)

## 6 Conclusions

The elastic modulus is stress state sensitive after springback, whereas the elastic modulus evolutive model is currently fitted from hysteresis loops with direction change point close to 5 MPa. To demonstrate the benefits of a model with a better consideration of the internal stress state evolution during springback, a linear elastic model with a 2-stage springback was presented before a full model implementation. The springback prediction of U-form (low BHS) application shows no interest, because despite different modulus of elasticity distributions, the 2 models predict the same profile positioned between the 2 constant value cases.

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