

# Development of the User Subroutine Library "Unified Material Model Driver for Plasticity (UMMDp)" for Various Anisotropic Yield Functions

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**Abstract.** Many yield functions have been proposed in academia to describe the complicated shapes of yield surfaces of metals. However, many of the commercial FEM codes provide only classical yield functions. Moreover, it takes a long time for engineers to implement newly proposed yield functions to commercial FEM codes. The Japan Association for Nonlinear CAE (JANCAE), a non-profit organization, developed the Unified Material Model Driver for plasticity (UMMDp) subroutine suite with the cooperation of industry users of CAE and the engineers of software vendors. This subroutine provides several anisotropic yield functions, and is applicable to most of the commercial FEM codes. The users can implement their own anisotropic yield functions easily using the UMMDp. This paper presents the basic framework of UMMDp and the development activities performed with many volunteers.

## 1. Introduction

A sheet metal has anisotropic plastic properties depending on the manufacturing processes. The properties of plasticity are represented as a yield function in numerical simulations. The relationship between the stress components of the material in the plastic state and the direction of the plastic strain increment is described by the yield function under the assumption of associated flow rule.

Therefore, to accurately simulate the plastic deformation of sheet metals in forming processes, an appropriate anisotropic yield function that can accurately reproduce the plastic deformation of real sheet metals must be adopted. In the past, many types of anisotropic yield functions have been proposed to describe the plastic deformation properties of sheet metals [1].

Several anisotropic yield functions have been built into the commercial finite element (FE) codes that are customized for the forming process simulations of sheet metals [2]. On the other hand, the general-purpose FE codes include a few anisotropic yield functions that are usually limited to only



In this paper, the development of a user-subroutine library for anisotropic plasticity models, which is commonly applicable to major commercial FE codes, is presented. The framework of the library is proposed, and a simple verification test using the proposed subroutine is presented.

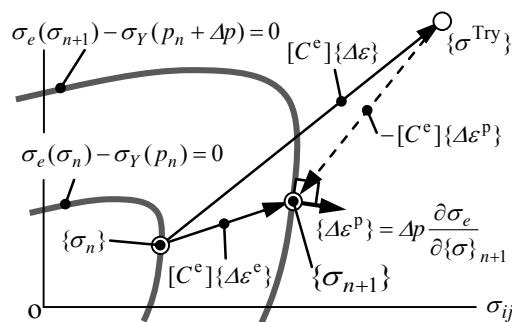
The typical nonlinear FE codes that deal with elastoplastic deformation employ the hypoelastic-type material model. **Figure 1** shows the role of the hypoelastic model in the FE codes. The material model in FE codes has two roles: stress integration and derivation of the consistent tangent modulus. They are calculated in each integration point of the elements every iterations. The main routine of the FE code evaluates the equilibrium of the overall structure using the updated stress state. If the norm of the residual force is unacceptable, a modified displacement field that reduces the residual force is predicted by the Newton–Raphson method using the consistent tangent modulus.

### 2.1 Basic equations for the backward Euler scheme

In the backward Euler scheme, all the equations describing the plastic deformation are satisfied in the end of the increment  $n+1$ . The status for which the stress in the increment  $n+1$ ,  $\{\sigma_{n+1}\}$ , must be located on the subsequent yield surface is represented by

Here, the type of the yield function  $\sigma_e$  is arbitrary,  $p_{n+1} = p_n + \Delta p$  is the equivalent plastic strain in increment  $n+1$ , and  $\sigma_Y(p)$  is the isotropic hardening function driven by  $p$ . Assuming the associated flow rule, the plastic strain increment  $\{\Delta \varepsilon^p\}$  is expressed as

The direction of the plastic strain increment coincides with the outward normal to the subsequent yield surface of increment  $n+1$ . The vector  $\{N\}$  represents the first order partial derivative of the yield function  $\sigma_e$  with respect to the stress components.



**Figure 2.** Schematic illustration of stress integration in backward Euler scheme

If the elastic strain is small enough, the additive decomposition of the elasto-plastic strain increment can be applied. The elastic strain increment  $\{\Delta\epsilon^e\}$  can be written as

$$\{\Delta\epsilon^e\} = \{\Delta\epsilon\} - \{\Delta\epsilon^p\}. \quad (3)$$

Thus, the stress in increment  $n+1$  can be written as

$$\{\sigma_{n+1}\} = \{\sigma_n\} + [C^e]\{\Delta\epsilon^e\} = \{\sigma_n\} + [C^e]\{\Delta\epsilon\} - \Delta p[C^e]\{N_{n+1}\} \equiv \{\sigma^{\text{Try}}\} - \Delta p[C^e]\{N_{n+1}\}. \quad (4)$$

Here,  $[C^e]$  is the matrix of the generalized Hooke's law. The trial stress  $\{\sigma^{\text{Try}}\}$  is the tentative stress state in which the total strain increment is assumed to be elastic.

The equations (1) and (4) are the base relations for stress integration in the backward Euler scheme. The schematic illustration of stress integration is shown in **Figure 2**.

## 2.2 Stress Integration

In stress integration, the stress increment  $\{\Delta\sigma\}$  and increment of the equivalent plastic strain  $\Delta p$  are solved to satisfy the equations (1) and (4). First, the residual scalar  $g_1$  and vector  $\{g_2\}$  from the equations are defined as

$$g_1 = \sigma_e(\sigma_{n+1}) - \sigma_Y(p_n + \Delta p), \quad (5)$$

$$\{g_2\} = \{\sigma_n\} + \{\Delta\sigma\} - \{\sigma^{\text{Try}}\} + \Delta p[C^e]\{N_{n+1}\}, \quad (6)$$

respectively.  $g_1$  and  $\{g_2\}$  must be converged to zero by the Newton–Raphson iteration.

To obtain the correction of the stress and equivalent plastic strain ( $\{\delta\Delta\sigma\}$  and  $\delta\Delta p$ ) in the Newton–Raphson iteration, equations (5) and (6) are linearized as follows.

$$g_1 + \{N\}^T \{\delta\Delta\sigma\} - \frac{\partial\sigma_Y}{\partial p} \{\delta\Delta p\} = 0, \quad (7)$$

$$\{g_2\} + [E]\{\delta\Delta\sigma\} + \delta\Delta p[C^e]\{N\} = 0. \quad (8)$$

Here, the subscript  $n+1$  is omitted.  $[E]$  is expressed as follows.

$$[E] = [I] + \Delta p[C^e] \frac{\partial\{N\}}{\partial\{\sigma\}^T}. \quad (9)$$

$[I]$  is the unit matrix. In the linearization, the strain increment  $\{\Delta\epsilon\}$  is not treated as variable, because  $\{\Delta\epsilon\}$  is given explicitly in the stress integration.

Solving the simultaneous equations (7) and (8), the correction for  $\Delta p$  and  $\{\Delta\sigma\}$  are obtained as

$$\delta\Delta p = \frac{g_1 - \{N^p\}^T [E]^{-1} \{g_2\}}{\{N\}^T [E]^{-1} [C^e] \{N\} + \frac{\partial\sigma_Y}{\partial p}}, \quad (10)$$

$$\{\delta\Delta\sigma\} = -[E]^{-1} \{\{g_2\} + \delta\Delta p [C^e] \{N\}\}. \quad (11)$$

The updates,  $\{\Delta\sigma\} + \{\delta\Delta\sigma\}$  and  $\Delta p + \delta\Delta p$ , are iterated until the residuals  $g_1$  and  $\{g_2\}$  are converged.

## 2.3 Consistent tangent modulus

The consistent tangent modulus is used to assemble the stiffness matrix of the overall structure and must be consistent with the algorithm of the stress integration scheme to obtain the quadratic

convergence in the structural equilibrium. This matrix is necessary for the static/implicit FE code and is not required in the dynamic/explicit one.

The consistent tangent modulus can be obtained by deriving the relation between the perturbations of the stress and strain increments,  $\{\delta\Delta\sigma\}$  and  $\{\delta\Delta\varepsilon\}$ . Here, the strain increment  $\{\Delta\varepsilon\}$  is treated as a variable to derive the consistent tangent modulus in contrast to the above mentioned stress integration. The total differentials of equations (1) and (4) are as follows.

$$\{N\}^T \{\delta\Delta\sigma\} - \frac{\partial\sigma_Y}{\partial p} \delta\Delta p = 0, \quad (12)$$

$$\{\delta\Delta\sigma\} = [C^e] \{\delta\Delta\varepsilon\} - [C^e] \left\{ \delta\Delta p \{N\} + \Delta p \frac{\partial\{N\}}{\partial\{\sigma\}^T} \{\delta\Delta\sigma\} \right\}. \quad (13)$$

The equation can be solved as follows.

$$\{\delta\Delta\sigma\} = \left[ [e] - \frac{[e] \{N\} \{N\}^T [e]}{\{N\}^T [e] \{N\} + \frac{\partial\sigma_Y}{\partial p}} \right] \{\delta\Delta\varepsilon\}. \quad (14)$$

Here,  $[e] = [E]^{-1} [C^e]$ . From the above, the integration of the stress and the derivation of the consistent tangent modulus can be achieved if only the yield function and its first and second order partial differentials are given.

### 3. Framework of the UMMDp

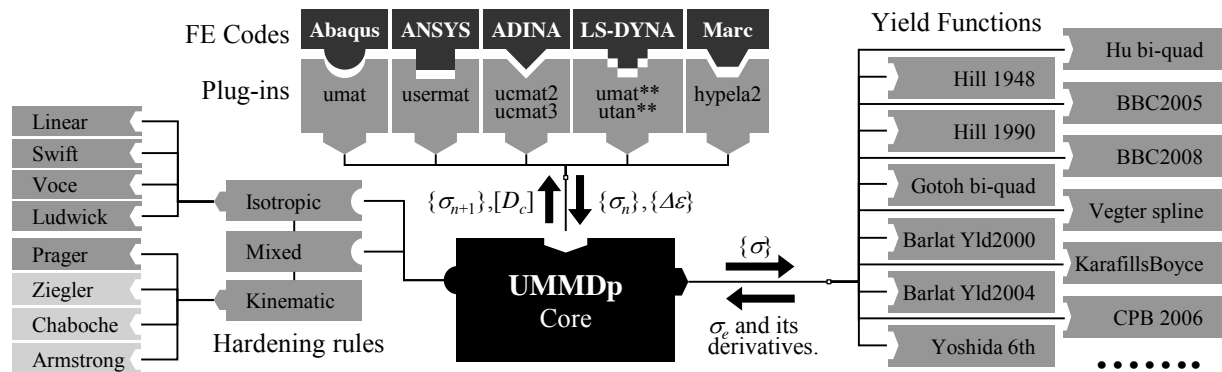
As mentioned above,

- (1) The roles of the material model user-subroutine for the hypoelastic constitutive model are common for all commercial FE codes.
- (2) In the stress integration and derivation of the consistent tangent, the yield function and its first and second order partial differentials are required. However, other numerical procedures are common and independent of the type of yield function.

From these two features, the material model can be unified as the common part of the numerical procedure, which externalizes the many types of FE codes and yield functions.

**Figure 3** shows the framework of the Unified Material Model Driver for plasticity (UMMDp). The center of the structure is a core program, which is the common part of the numerical procedure in elasto-plastic calculations.

This core program is called from the user-subroutines of each FE code. Each user-subroutine has the role of a “plug-in” that connects the UMMDp core to the FE code. The user-subroutine converts



**Figure 3.** Framework of Unified Material Driver for plasticity (UMMDp).

the variables of each FE code to common forms for the core of the UMMDp.

In the branches on the right of figure 3, the various yield functions are modularized as subroutines in which the yield function and its first and second partial differentials are calculated as the arguments for the core program. Furthermore, as shown in the branches on the left of figure 3, the various hardening rules, including the kinematic and combined hardening models, are modularized for the future expansion.

The user-subroutine library of the UMMDp is independent of the specific FE codes and provides wide expandability for various yield functions to users.

#### 4. Collaborative activity in JANCAE

**Table 1** lists the variables in the user-subroutines for the hypoelastic material model in the various major FE codes. The names and the array types of variables differ depending on the codes, but an obvious similarity is seen in this list. The detailed applications of the user-subroutine to the commercial FE codes are discussed in the individual conferences held by the software vendors.

The Japan Association for Nonlinear CAE (JANCAE) is a nonprofit organization [4]. A major activity of JANCAE is to offer the Nonlinear CAE training course, which is held twice a year to further a users' understanding of CAE. A total of approximately 5,000 engineers participated in this training course from 2001 to 2017. From 2005, JANCAE also organized the "Material Modeling Working Group", in which more than 30 engineers and researchers from universities, private companies, and software vendors participate every year.

All the programs of the UMMDp were developed by the participants of the material modeling working group on a volunteer basis. In particular, the 'plug-in' subroutines were programmed by the technical support engineers of the software vendors. Owing to this plug-in, the UMMDp is applicable to Abaqus, ANSYS, ADINA, LS-DYNA and Marc. On the other hand, the modules of the anisotropic yield functions were programed by the CAE users of the manufacturing industries. The following yield functions proposed in the past were implemented in the UMMDp: Hill's 1948 [3] and 1990 [5], Gotoh's bi-quadratic [6], Hu's bi-quadratic [7], Yoshida's sixth order polynomial [8], Bralat's Yld89 [9], Yld2000-2d [10], and Yld2004 [11], Banabic's BBC2005 [12] and BBC2008 [13], Cazacu's CPB2006 [14], Karafillis & Boyce [15], and Vegter's spline function [16].

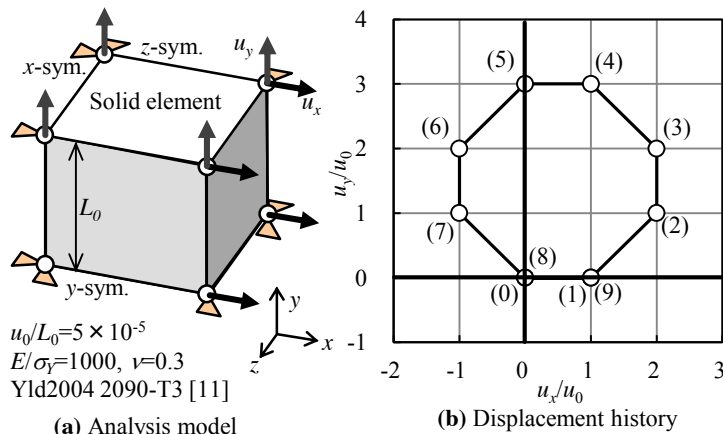
#### 5. Simple verification test of UMMDp

Here, we show that the UMMDp works accurately in FE codes by a simple verification test. The boundary condition and material properties for the test are shown in **Figure 4(a)**. The flow stress is constant (perfectly plastic) and Young's modulus is sufficiently large compared to the flow stress. Figure 4(b) shows the displacement history given to the element. The stress point analyzed in the FE code should trace the prescribed yield locus because of the assumption of associated flow rule [17]. The analyzed stress point converges to the point, at which the outward normal to the yield locus coincides with the direction of the plastic strain increment.

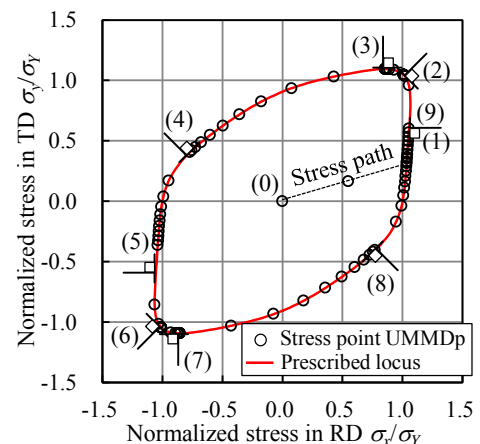
In **Figure 5**, the solid line shows the prescribed yield locus defined by Yld2004 [11] and the plots show the stress points analysed with UMMDp. The accuracy of UMMDp is verified by the exact

**Table 1.** List of representative variables in general purpose FE codes.

Code	Abaqus	ADINA	ANSYS	LS-DYNA	Marc
User subroutine	umat	ucmat2/3	usermat	umat/utan	HYPELA2
Stress	STRESS	stress	stress	sig	S
Strain increment	DSTRAN	deps	dStrain	eps	DE
Consistent tangent	DDSDDE	d	dsdePl	es	D
Number of stress comp.	NDI, NSHR	Fixed.	nDirect, nShear	Refer to 'eltype'	NDI, NSHEAR
State variable	STATEV	ARRAY	ustatev	hsv	T,DT
Number of state var.	NSTATEV	LGTH1	nStatev	nhv	NSTATS
Exit code	XIT	END	EXIT	Adios	QUIT



**Figure 4.** Analysis condition for simple verification test.



**Figure 5.** Verification of UMMDp

agreement of the stress plots with the prescribed yield locus. In addition to the simple verification, the participants to the working group cooperated to solve the practical sheet forming problems as the working examples of UMMDp.

## 6. Conclusion

The development of a user-subroutine library for various anisotropic yield functions is introduced. This library is applicable to major FE codes. By using this library, FE users can implement recently proposed or their own yield functions to the FE code easily.

The UMMDp and some example input data files are open to the public on the website [4].

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