NPO Activity for Implementation of Anisotropic Elasto-plastic Models into Commercial FEM Codes

The nonprofit organization JANCAE, The Japan Association for Nonlinear CAE (chairperson: Kenjiro Terada, Tohoku University), offers several activities to companies, universities and software vendors [1] to gain a deeper understanding of nonlinear CAE including its main work, the nonlinear CAE training course held twice a year. This article introduces JANCAE's efforts to implement anisotropic elasto-plastic models into commercial FEM codes as one of the initiatives of the "Material Modeling Committee".

2. Background and outline

2.1 The efforts of the Material Modeling Committee:

When we think of comprehensive advancements in the accuracy of a simulation, we are aware that all capabilities of the material modeling, the boundary conditions as well as the definition of the geometric modeling have to be improved at the same level. The capabilities of geometric modeling for FEM simulations have drastically improved along with the growth of the 3D CAD market, the advancements in auto-meshing capabilities and the progresses made in hardware speeds and capacities, over the past 10 years. Yet material modeling capabilities have not progressed as significantly as the advances achieved in geometric modeling. Users need to be involved in the definition process of material modeling, which means that they have to choose the appropriate material model from huge amounts of available material models offered by each FEM code. As a next step, the parameters of the material properties have to be determined by performing material tests. These processes are still necessary, even now, at a time when many sophisticated commercial FEM codes are available.

In this situation and independently from its CAE training course, which mainly consists of classroom lectures, JANCAE organizes "The Material Modeling Committee" as a practical approach to the study of nonlinear materials. The Committee was originally established in 2005 to study mainly hyperelasticity and viscoelasticity. Then, its research activities have diversified into all material nonlinearity including metal plasticity. In the frame of the Committee, members learn about typical nonlinear material modeling by studying the basic theory of the constitutive equations, material testing methods, and how to handle test data and parameter identification techniques.

2.2 User subroutines for constitutive law in FEM Codes

There are many constitutive equations of materials, as we can see from the many researchers' names which appear in the titles of the equations. Although such variety of material models contributes to the improvement of simulation accuracy, not all material models, especially new models, can be applied to various commercial FEM codes. With regard to yield functions, which are a core concept for metal plasticity, it has been pointed out that the yield surfaces of the actual metal materials cannot be represented well enough by the classical anisotropic yield functions [2]. However now, many different types of new yield functions are proposed especially in sheet metal forming; they are able to represent real plastic deformation much better than before [3].

LS-DYNA provides specific capabilities for sheet metal forming simulation, it also offers a considerable number of new anisotropic yield functions [4]. On the other hand, when we think about other commercial general purpose FEM codes, they usually have only limited kinds of yield functions, such as the classical Hill quadratic anisotropic function.

These commercial codes offer user subroutine capabilities to extend material models. By using these capabilities and defining material models following the programming rules that each code provides, users can implement the required constitutive laws. However in reality, it is difficult for ordinary users who are not familiar with the framework of continuum mechanics, numerical simulation and the theory of plasticity, to perform such processes only from released text books or available information, as the manual definition in FEM codes requires professional skills.

2.3 The development activity in the Material Modeling Committee

The Material Modeling Committee started its unique R&D activity in 2009. For this activity, engineers with various backgrounds and skills engaged in the CAE field got together to jointly work on making subroutines for the constitutive laws. The members are from industrial companies and CAE software vendors.

As mentioned above, it is impossible to create such subroutines without understanding the basic concept of elasto-plastic models for FEM. In the first year, in 2009, we studied the basics of plastic constitutive equations and the framework

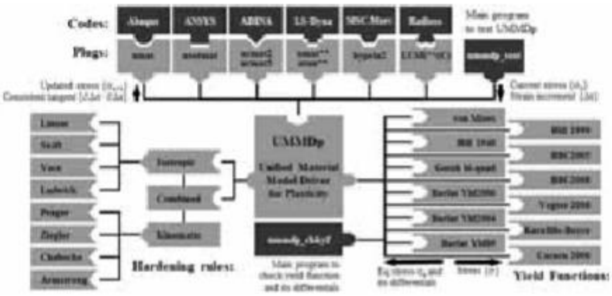


Fig. 1 - Framework of the subroutine "UMMDp"

of constitutive law subroutines by referring to some text books [5], to obtain a better understanding of their principles. In parallel, we summarized the characteristics of each code's user subroutine and proposed a framework for the user subroutine development. [Fig.1] In this framework, stress integration and calculation of consistent tangent modulus, which represent basic capabilities of constitutive law subroutines, have been determined as "Unified Material Model Driver for Plasticity (UMMDp)" and separated from each code's specified rule in order to be able to be used commonly. Additionally, yield functions were isolated as a modularized subroutine so that we can implement different types of yield functions easily. In the second year, in 2010, the members worked on the programming based on this framework and by sharing each role.

3. Development and verification of the user subroutine

3.1 Basic equations of elasto-plastic constitutive laws

Here we show the basic part of the subroutine for elasto-plastic constitutive laws, which is crucial for this programming.

Tensor is represented by the Voigt notation arraying components as vector. The stress to be calculated is $\{\sigma\}$, and the strain increment given to the subroutine is $\{\Delta\varepsilon\}$. Following are basic equations for elasto-plastic constitutive laws.

$$\sigma_e(\sigma - X) - \sigma_Y(p) = 0 \tag{1}$$
$$\{\Delta\varepsilon\} = \{\Delta\varepsilon^e\} + \{\Delta\varepsilon^p\} \tag{2}$$
$$\{\Delta\sigma\} = [D^e]\{\Delta\varepsilon^e\} \tag{3}$$
$$\{\Delta\varepsilon^p\} = \Delta p \bullet \{\partial\sigma_e / \partial(\sigma - X)\} \tag{4}$$
$$\{\Delta X\} = \Delta p \bullet \{V(\sigma, X, p)\} \tag{5}$$

Equation (1) shows the yield condition and represents that stress point on the yield surface. The shape of the yield surface is determined by the yield function σ_e, the magnitude is given by the hardening curve $\sigma_y(p)$ showing isotropic hardening and the center of the yield surface is provided by the back stress $\{X\}$ showing kinematic hardening respectively. Equation (2) shows that the elastic and the plastic strain increments are given by additive decomposition, and the elastic strain increment $\{\Delta\varepsilon^e\}$ gives the stress increment $\{\Delta\varepsilon^p\}$ by Hooke's law shown as Equation (3). Equation (4) gives the plastic strain increment $\{\Delta\varepsilon^p\}$ and here the associated flow rule is used, in which the outward normal of the yield surface and the plastic strain increment have the same direction. Equation (5) is the evolution equation of the back stress. p shows the equivalent plastic strain which has a conjugate relation with the equivalent stress σ_e in the plastic work. UMMDp uses backward Euler's method for the stress integration algorithm. In this method, nonlinear simultaneous equation is solved, assuming the stress $\{\sigma_{n+1}\}$ and internal variable (back stress $\{X_{n+1}\}$ and equivalent plastic strain p_{n+1}) after the completion of "n+1" increment satisfy the basic equations (1) – (5). We now define residual functions as follows.

$$g_1 = \sigma_e(\sigma_{n+1} - X_{n+1}) - \sigma_Y(p_n + \Delta p) \tag{6}$$
$$\{g_2\} = \{\sigma_{n+1}\} - \{\sigma^{Try}\} + \Delta p[D^e]\{\partial\sigma_e / \partial(\sigma_{n+1} - X_{n+1})\} \tag{7}$$
$$\{g_3\} = \{X_{n+1}\} - \{X_n\} - \Delta p\{V(\sigma_{n+1}, X_{n+1}, p + \Delta p)\} \tag{8}$$

Now $\{\sigma^{Try}\}$ is the trial stress (initial estimate of stress integration) assuming all strain increments are elastic components and given by

$$\{\sigma^{Try}\} \equiv \{\sigma_n\} + [D^e]\{\Delta\varepsilon\}$$

Equation (6), Equation (7) and Equation (8) correspond to the yield condition of Equation (1), Equation (2) – (4) and the back stress evolution equation of Equation (5) respectively, and the stress after integration $\{\sigma_{n+1}\}$ and the internal variable ($\{X_{n+1}\}$ and p_{n+1}) are obtained by converging g_1, $\{g_2\}$ and $\{g_3\}$ to 0 using Newton-Raphson method. In UMMDp, it is predicted that the convergence calculation will be difficult because of implementation of higher order anisotropic yield functions. So we relaxed the condition of (6) by using Multi-stage Return Mapping [6] which leads to gradual convergence.

3.2 The idea of UMMDp

The variables used for convergence calculation of the stress integration are the yield function $\sigma_e(\sigma)$, the isotropic hardening curve $\sigma_y(p)$, the back stress evolution equation $\{V(\sigma, X, p)\}$ and their first and second order differentials. In the static implicit method, tangent matrix (Material Jacobian) consistent with stress integration algorithm, is also required to obtain the quadratic convergence in equilibrium calculation. In this calculation, as with the stress integration, yield function, isotropic hardening curve, back stress evolution equation value and its differential value are going to be needed. The frameworks of calculation for stress integration and consistent tangent modules are in common regardless of forms of yield function, hardening curve and back stress evolution equation. Therefore, if we could make a unified interface for those various sets of functions, the function group of a variety of constitutive equations described above would be able to be modularized and have higher expandability. When we think about the variable names and the stored formats in subroutines of commercial codes, of course they vary from code to code. However, the role of the constitutive law in FEM codes is to provide "local stress-strain relation at integration point" and there is no difference on this point. By using proper variable conversion for code-independent user subroutines, they can be linked to UMMDp correctly. From this standpoint, the great variety of constitutive equations, such as yield function and hardening law can be externalized. Additionally, if we develop the interface for different commercial codes using their specific user subroutines, which we call "Plug", it will kick-off an open effort and a discussion which will not be limited to a specific code.

3.3 Yield function subroutine

The yield function subroutine is developed mainly by CAE users from industrial companies. Following are the yield functions for the implementation. (von Mises is used for verification of the implementation.)

von Mises[7]

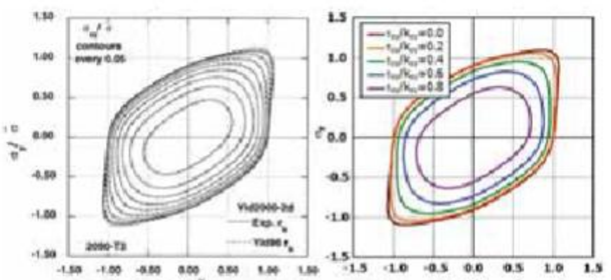
Hill(1948[8], 1990[9])

Gotoh's bi-quadratic yield function [10]
Barlat yield function (Yld89[11], Yld2000[12], Yld2004[13])
Banabic yield function (BBC2005[14], BBC2008[15])
Cazacu 2006[16]
Karafills & Boyce[17]
Vegter[18]

The yield function subroutine receives the stress component $\{\sigma\}$ as the argument, and then returns the corresponding equivalent stress σ_e, its first order differential $\partial\sigma_e/\partial\{\sigma\}$ and its second order differential $\partial^2\sigma_e/\partial\{\sigma\}\partial\{\sigma\}^T$.
To demonstrate objectively that the developed subroutine works correctly, also numerical verification is being performed. For this verification, we also provide a main routine so that only the capability of the yield function's subroutine itself can be checked separately without mixing up its bug with other bugs in UMMDp (the parent routine of the yield function's subroutine), and "Plug" for commercial FEM codes. By doing so, the members can work independently. The verification was performed by the comparison between the yield surface in the original paper, which proposed anisotropic yield functions, and the output from our developed subroutine as shown in Fig.2, as well as by the comparison between analytical and numerical differential values to secure correctness.

3.4 Development of the interface "Plug" for commercial codes

The "Plug" subroutine, which becomes an interface to commercial FEM codes, is developed mainly by engineers from CAE software vendors. This subroutine links to UMMDp correctly through each different manner depending on commercial codes. The name of the 'Plug' is based on the functional analogy of plug-adopter for AC power socket which differs by nation.
The Plug needs to offer overall capabilities for communication with commercial codes, such as storing and updating internal variables, and variable output adjustment to result data. On this point, it was very helpful to gain the cooperation of engineers from software vendors, who are familiar with each commercial code. We appreciated their cross-border cooperation.
The verification of the developed Plug was also performed. For this verification, we used the basic benchmark test provided by the NAFEMS guidebook [19] for "Code to Code Verification". We compared the result using default elasto-plastic models prepared in each commercial code (von Mises type isotropic yield functions) and the result using the von Mises type yield function through UMMDp, and we confirmed that these stress histories are matching as shown in Fig.3.



(a) Yield locus in original paper [12] *(b) Output from ummdp_checkyf*

Fig. 2 - Verification of yield function subroutine (eg. Yld2000).

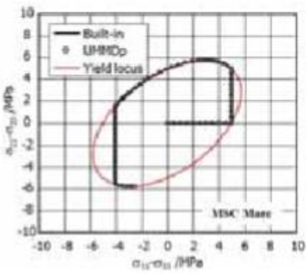


Fig. 3 - Comparison with result of commercial code (von Mises model)

3.5 Implementation of combined hardening law

We finalized the development and the verification of the program for the standard isotropic hardening models in 2009. It is difficult to simulate deformation behavior accurately when the direction of stress is reversed. So we are promoting the development of the combined hardening model including kinematic hardening shown in the basic equations. Kinematic hardening behavior is modeled by back stress evolution equation. For this evolution equation, various types of models are proposed, and we need to accept this diversity as with yield functions. At this point in time, we are developing a framework to modularize the function $\{V(\sigma, X, p)\}$ shown in Equation (5) as a subroutine.

3.6 Total verification

For total verification of the developed program, we analyzed problems which come to the surface by the influence of plastic anisotropy, and we compared them to the reliable result. We simulated a hole-expansion test of a steel sheet [20] and a hydraulic bulge test of aluminum alloy [21] in cooperation with Prof. Kuwabara, Tokyo University of Agriculture and Technology. Fig.4 shows the simulation result of the hole-expansion test. We can see that the thickness decrease around the center hole varies with angle from the rolling direction. Afterwards, we verified that the developed subroutine group worked rightly, by comparing the UMMDp simulation result and the reliable simulation result. The aim of the verification at this stage is not the comparison with experimental results, instead it is absolutely for Code to Code Verification. We think that using the middle scale problem, which is positioned between small scale problems like material testing and large scale problems in realistic sheet metal forming, is more important for the material model validation rather than jumping to a complicated large scale problem.

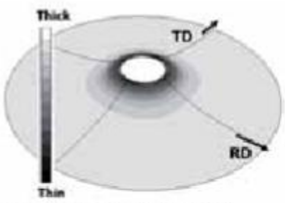


Fig. 4 - Simulation example of hole-expansion test

4. Closing

In this article, we introduced an activity of the NPO "JANCAE" working group. As the volume of tasks becomes larger, the development is still in progress. In 2011, the development of a common subroutine for resin and rubber has been planned as a subsequent activity of the working group. The effort this time is the implementation of the yield functions which were already proposed in previous papers, hence there is no academic novelty. Meanwhile, it is not just about a limited activity for a specific commercial code only. This is why the topic is not really suitable to be presented in academic societies or at specific users' conferences by CAE vendors. We introduced this work as an example of the activities featuring NPO's neutrality. Following NPO's guidelines, it is planned that the subroutine group will be opened to the public a year after activity completion. Yet more than 30 engineers from different organizations have already joined the working group. Their backgrounds are different, some have already obtained permissions from their managers, some join to support their own personal development. In any case, their motivation is the most important driving force for the activity.

C.A Coulomb, when he was a building engineer in the military corps of engineers, expressed the reason to write a paper by making an analogy to an artisan when he submitted the paper to the French Académie des sciences in 1773, as follows.[22]

"Besides, the Sciences are monuments consecrated to the public good. Each citizen ought to contribute to them according to his talents.... While great men will be carried to the top of the edifice where they can mark out and construct the upper stories, ordinary artisans who are scattered through the lower stories or hidden in the obscurity of the foundations should seek only to perfect that which cleverer hands have created." We think the reason why so many engineers were eager to be involved in the work is because of their motivation to understand in a deeper way and to express their sympathy for the activity based on Coulomb's words. We, ordinary artisans, have great responsibility in the present apprehensions regarding the gap between computational mechanics and CAE [23].

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