ABAQUS用户定义单元UEL与VUEL从入门到放弃系列2

ABAQUS User-Defined Element UEL and VUEL from Beginner to Abandonment Series 2

借风一尺 Borrowing a Foot of Wind

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大家好，我是借风一尺，一个终极懒癌患者。 Hello everyone, I am Jiefeng Yizhi, a chronic ultimate laziness patient.

……说完这句话其实已经不想再码字了。 ......After saying this sentence, I actually didn't want to type anymore.

好的，直入主题，速战速决。 Good, let's get straight to the point and finish quickly.

来技术邻其实已经很久了，也目睹了技术邻这两年飞一般的发展速度，好像突然火起来了哈哈。最初来技术邻，讲实话其实就是来学UEL的，后来发现没帖子，然后就各种找论坛，simweABAQUS版块的帖子二零零几年的帖子都被我挖干净了，做UEL的人确实比做UMAT的少多了，但技术邻这个平台依旧让我受益良多，诸如蓝牙老师，isolver团队snowwave02等大佬，他们的分享，甚至很多是免费分享确实高屋建瓴，知识的学习必是知其所以然，我想只有这样的学术氛围越来越重，这样乐于分享的大佬越来越多，中国的自研工业软件才能走向世界，我们的工业4.0才有可能实现。

I have been on Technical Neighbor for a long time, and I have witnessed the rapid development of Technical Neighbor over the past two years, as if it has suddenly become popular, hahaha. Initially, I came to Technical Neighbor to learn UEL, but later I found that there were no posts, so I searched various forums, and I have combed through the posts in the simweABAQUS section from the year 2000, and there are indeed fewer people doing UEL than those doing UMAT, but this platform of Technical Neighbor has still benefited me a lot. People like Bluetooth teacher, isolver team snowwave02, and other big shots, their sharing, even many of which are free, are indeed high-level. The learning of knowledge must be to understand the reasons behind it. I believe that only when such an academic atmosphere becomes stronger and more big shots like these are willing to share, can China's independently developed industrial software go global, and our Industrial 4.0 can be realized.

学于此，也该传于此，作为一只科研狗，我想我比谁都清楚什么叫从“入门”到“放弃”，未知的知识就是这样，不懂的时候它比金子都贵，等你学会了它好像又像水一样普通，亦如水一样珍贵。

Learning here, I should also pass on my knowledge here. As a research dog, I think I know more than anyone else what it means to go from "beginning" to "giving up." Unknown knowledge is like gold to those who don't understand it, but once you learn it, it seems as ordinary as water, yet as precious as water.

之后也会逐渐在技术邻更一些帖子，可能也会有视频吧，内容大概会围绕有限元理论，用户子程序开发，ABAQUS python开发，XFEM，lamb波的SHM等，因为不知道想学UEL\VUEL的人群多大，也不知道大家都想了解些什么，不知道应该从何说起，可能有些想学UEL的小白基础很差连有限元理论都没学全，再加上我确实是个懒癌晚期，其实很多东西都做好了，懒的发，也希望能治疗一下自己的懒癌吧。

I will also gradually post some articles on Technical Neighbor, and may also have some videos. The content will mainly be about finite element theory, user subroutine development, ABAQUS Python development, XFEM, Lamb wave SHM, etc. Because I don't know how many people want to learn UEL\VUEL, nor do I know what everyone wants to know, and I don't know where to start. Perhaps some beginners in UEL have a very poor foundation and haven't even learned the whole finite element theory. In addition, I am indeed in the late stage of laziness, and I have actually prepared a lot of things, but I am too lazy to post them. I also hope to cure my laziness.

今日份正事，给大家简单讲一讲ABAQUS中的压电耦合单元C3D8E。

Today's task, let's briefly introduce the piezoelectric coupling element C3D8E in ABAQUS.

那么什么叫压电耦合单元呢，简单的说就是你给它加载电压（电势的差，ABAQUS中为位移加载），那么就会引起单元力学场的变化，比如位移、应力、应变等等；同样的你给它加载力或者位移，亦会引起单元电场的变化。

So what is a piezoelectric coupling element? Simply put, when you apply a voltage (the difference in potential, displacement loading in ABAQUS), it will cause a change in the element's mechanical field, such as displacement, stress, strain, etc.; Similarly, applying force or displacement to it will also cause a change in the element's electric field.

单元压电耦合场的广义本构方程表示如下： The general constitutive equation of the element's piezoelectric coupling field is as follows:

$$\begin{Bmatrix} \{\sigma\} \\ \{D\} \end{Bmatrix} = \begin{bmatrix} [C] & [e]^{\top} \\ [e] & \left[-\varepsilon^{\varepsilon}\right] \end{bmatrix} \begin{Bmatrix} \{\varepsilon\} \\ \{-E\} \end{Bmatrix}$$

即为：广义应力=广义弹性矩阵·广义应变。其中广义力中D为电位移，广义应变中E为电场强度。

That is: generalized stress = generalized elastic matrix · generalized strain. Among the generalized forces, D represents the electric displacement, and among the generalized strains, E represents the electric field intensity.

在广义弹性矩阵中，C矩阵为力学场的弹性矩阵，e矩阵为压电常数矩阵，右下角为介电常数矩阵。亦可展开如下表示（某种材料的参数，如果是特殊材料e矩阵中非0常数会更多或者更少，由材料本身决定）。

In the generalized elastic matrix, the C matrix is the elastic matrix of the mechanical field, the e matrix is the piezoelectric constant matrix, and the lower right corner is the dielectric constant matrix. It can also be expanded as follows (parameters of a certain material; if it is a special material, there may be more or fewer non-zero constants in the e matrix, which is determined by the material itself).

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{13} \\ \sigma_{23} \\ \sigma_{12} \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ c_{12} & c_{22} & c_{23} & 0 & 0 & 0 \\ c_{13} & c_{23} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \gamma_{13} \\ \gamma_{23} \\ \gamma_{12} \end{bmatrix} - \begin{bmatrix} 0 & 0 & e_{31} \\ 0 & 0 & e_{31} \\ 0 & 0 & e_{33} \\ 0 & e_{15} & 0 \\ e_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & e_{15} & 0 \\ 0 & 0 & 0 & e_{15} & 0 & 0 \\ e_{31} & e_{31} & e_{33} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \gamma_{13} \\ \gamma_{23} \\ \gamma_{12} \end{bmatrix} + \begin{bmatrix} \lambda_{11} & 0 & 0 \\ 0 & \lambda_{22} & 0 \\ 0 & 0 & \lambda_{33} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

本构关系的张量表达式为： The tensor expression of the constitutive relationship is:

$$\sigma_{ij} = D^{E}_{ijkl}\varepsilon_{kl} - e^{\varphi}_{mij}E_m$$
$$D_i = e^{\varphi}_{ijk}\varepsilon_{jk} + D^{\varphi(\varepsilon)}_{ij}E_j$$

其中，广义应变的有限元格式可表示为： Among them, the finite element format of the generalized strain can be expressed as:

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{xz} \\ -E_x \\ -E_y \\ -E_z \end{bmatrix} = \begin{bmatrix} \frac{\partial}{\partial x} & 0 & 0 & 0 \\ 0 & \frac{\partial}{\partial y} & 0 & 0 \\ 0 & 0 & \frac{\partial}{\partial z} & 0 \\ \frac{\partial}{\partial y} & \frac{\partial}{\partial x} & 0 & 0 \\ 0 & \frac{\partial}{\partial z} & \frac{\partial}{\partial y} & 0 \\ \frac{\partial}{\partial z} & 0 & \frac{\partial}{\partial x} & 0 \\ 0 & 0 & 0 & \frac{\partial}{\partial x} \\ 0 & 0 & 0 & \frac{\partial}{\partial y} \\ 0 & 0 & 0 & \frac{\partial}{\partial z} \end{bmatrix} [N] \begin{Bmatrix} \{\delta\} \\ \varphi \end{Bmatrix}$$

其中，电场强度E为负的电势梯度： Among them, the electric field intensity E is the negative gradient of the electric potential:

$$E = -\nabla\varphi$$

则广义应变列阵记为： The generalized strain tensor is denoted as:

$$\begin{Bmatrix} \{\varepsilon\} \\ \{-E\} \end{Bmatrix} = \begin{bmatrix} B_u & 0 \\ 0 & B_v \end{bmatrix} \begin{Bmatrix} \{\delta\} \\ \varphi \end{Bmatrix}$$

那么，单元的刚度矩阵可以表示为： Then, the stiffness matrix of the element can be expressed as:

$$K = \oint_v B^{\top} DB dv = \oint_v \begin{bmatrix} Bu & 0 \\ 0 & B_V \end{bmatrix}^{\top} \begin{bmatrix} D_{uu} & D_{uv} \\ D_{vu} & D_{vv} \end{bmatrix} \begin{bmatrix} Bu & 0 \\ 0 & B_V \end{bmatrix} dv = \oint_V \begin{bmatrix} k_{uu} & k_{uv} \\ k_{vu} & k_{vv} \end{bmatrix} dv$$

其中Kuu为C3D8原本的刚度矩阵，Kuv与Kvu为压电耦合刚度矩阵，Kvv为电场的广义刚度矩阵。

Among them, Kuu is the original stiffness matrix of C3D8, Kuv and Kvu are the piezoelectric coupling stiffness matrices, and Kvv is the generalized stiffness matrix of the electric field.

ABAQUS中的C3D8和C3D8E都是做了一些刚度修正的，比如C3D8为了防止单元自锁，采用了B-Bar方法，得出的刚度矩阵是介于C3D8和C3D8R之间的值，同样的C3D8E也有一些类似的修正，以下我将提供一个不包含修正的版本，对ABAQUS刚度修正方法感兴趣的朋友可以去拿去跟ABAQUS CAE对比。

Both C3D8 and C3D8E in ABAQUS have made some stiffness corrections, such as C3D8 to prevent element locking, adopting the B-Bar method, resulting in a stiffness matrix between the values of C3D8