有限元理论基础及Abaqus内部实现方式研究系列3：S4壳单元剪切自锁和沙漏控制

Theoretical Foundation of Finite Element Method and Internal Implementation of Abaqus Series 3: Shear Locking and Shear Band Control of S4 Shell Element

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==概述== ==Overview==

在CAE领域，从学校、实验室的自研算法到实现真正的商业化软件是一条无比漫长的道路。我们不研究有限元的新方法、新理论，只是研究商用有限元软件的实现方式。有限元的理论发展了几十年已经相当成熟，商用有限元软件同样也是采用这些成熟的有限元理论，只是在实际应用过程中，商用软件在这些传统的理论基础上会做相应的修正以解决工程中遇到的不同问题，且各家软件的修正方法都不一样，每个主流商用软件手册中都会注明各个单元的理论采用了哪种理论公式，但都只是提一下用什么方法修正，很多没有具体的实现公式。

In the field of CAE, the journey from self-developed algorithms in schools and laboratories to the realization of truly commercial software is an incredibly long one. We do not research new methods or theories of finite elements, but rather study the implementation methods of commercial finite element software. The theoretical development of finite elements has matured for decades and commercial finite element software also adopts these mature finite element theories. However, in the process of practical application, commercial software will make corresponding corrections on the basis of these traditional theories to solve different problems encountered in engineering, and the correction methods of each software are different. Each mainstream commercial software manual will specify which theoretical formula each element uses, but only mention the correction method, and many do not provide specific implementation formulas.

商用软件对外就是一个黑盒子，除了开发人员，使用人员只能在黑盒子外猜测内部实现方式，一方面我们查阅Abaqus软件手册得到修正方法的说明，另一方面我们自己编程实现简单的结构有限元求解器，通过自研求解器和Abaqus的结果比较结合理论手册如同管中窥豹一般来研究Abaqus的修正方法，从而猜测商用有限元软件的内部计算方法。为了理解方便有很多问题在数学上其实并不严谨，同时由于水平有限也可能有许多的理论错误，欢迎交流讨

论。

Commercial software is essentially a black box to the outside, and users can only guess at the internal implementation methods from outside, except for developers. On one hand, we consult the Abaqus software manual for explanations of the correction methods, and on the other hand, we program simple structural finite element solvers ourselves. By comparing the results of our self-developed solver with those of Abaqus and combining theoretical manuals, we can study Abaqus' correction methods as if we were peering through a bamboo tube. This allows us to guess the internal calculation methods of commercial finite element software. For the sake of convenience in understanding, many issues are actually not mathematically rigorous, and due to our limited abilities, there may be many theoretical errors. We welcome discussions and exchanges.

==以往的系列文章==　　==Previous Series Articles==

第一篇：S4壳单元刚度矩阵研究 http://www.jishulink.com/content/post/338859

First Article: Research on the Stiffness Matrix of S4 Shell Element http://www.jishulink.com/content/post/338859

研究基于Mindlin厚壳理论的S4壳单元的刚度矩阵在Abaqus中的实现方式

Research on the Implementation of Stiffness Matrix of S4 Shell Element Based on Mindlin's Thick Shell Theory in Abaqus

第二篇：S4壳单元质量矩阵研究 http://www.jishulink.com/content/post/343905

Second Article: Research on the Mass Matrix of S4 Shell Element http://www.jishulink.com/content/post/343905

研究一致质量矩阵和集中质量矩阵在Abaqus的S4壳单元和Nastran的Quad4壳单元中的实现方式

Research on the Implementation of Consistent Mass Matrix and Concentrated Mass Matrix in Abaqus S4 Shell Element and Nastran Quad4 Shell Element

==第三篇：S4壳单元剪切自锁和沙漏控制==　　==Third Part: Shear Locking and Shear Band Control of S4 Shell Element==

商用有限元软件的健壮性体现在对各种特殊情况，求解过程和解的正确性依然能得到保证，而这些特殊情况在自编程序中如果没有考虑到，那么结果就可能相差极大。其中剪切自锁和沙漏现象是最常见的会影响正确性的两个特殊情况。这两者具有相似性，所以我们在本文中一起研究Abaqus中线性壳单元S4针对这两种情况下的内部实现方式。剪切自锁和沙漏现象影响的是刚度矩阵和应力，我们研究方式是在自编程序iSolver中根据成熟的消除剪切自锁和沙漏控制的理论实现刚度矩阵的修正，通过比较同一模型的Abaqus的刚度矩阵结果，结合帮助文档猜测Abaqus

软件单元消除剪切自锁和控制沙漏的内部实现方法。

The robustness of commercial finite element software is reflected in its ability to ensure the correctness of the solution process and the results even under various special cases. These special cases, if not considered in self-written programs, can lead to significantly different results. Among these, shear locking and hourglass phenomena are the most common special cases that can affect correctness. Both of these phenomena have similarities, so in this paper, we study the internal implementation methods of Abaqus linear shell element S4 for these two cases together. Shear locking and hourglass phenomena affect the stiffness matrix and stress, and our research method is to correct the stiffness matrix in the self-written program iSolver based on mature theories for eliminating shear locking and hourglass control. By comparing the stiffness matrix results of the same model from Abaqus, and combining with the help documentation, we guess the internal implementation methods of Abaqus software units for eliminating shear locking and controlling hourglass phenomena.

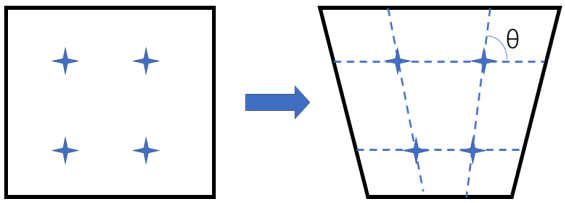

图1：剪切自锁　　Figure 1: Shear Locking

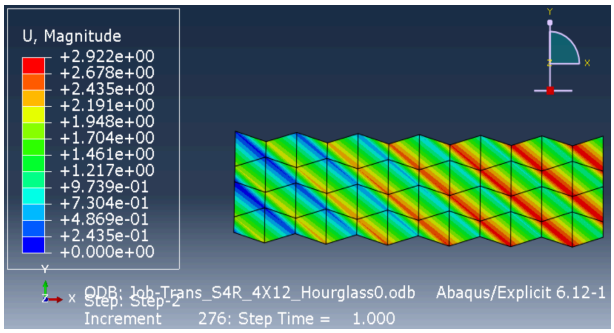

图2：沙漏　　Figure 2: Hourglass

===S4壳单元剪切自锁和沙漏控制研究总结===　　===Research Summary on Shear Locking and Hourglass Control of S4 Shell Element===

完全积分单元才有剪切自锁，虽然Abaqus的S4单元是完全积分，但内部已经做了修正完全消除了剪切自锁，所以不需要用户做任何设置。

Only fully integrated elements have shear locking. Although the Abaqus S4 element is fully integrated, internal corrections have been made to completely eliminate shear locking, so no user settings are required.

减缩积分单元才有沙漏现象，Abaqus的S4R默认增加一个人工的沙漏刚度来控制沙漏现象，如果发现结果还是不理想，那么需要采用其它建模方法才能控制沙漏了。

Only reduced integration elements have the phenomenon of hourglassing. The Abaqus S4R element defaults to adding an artificial hourglass stiffness to control hourglassing. If the results are still not satisfactory, then other modeling methods need to be adopted to control hourglassing.

Abaqus针对剪切自锁和沙漏控制做的修正如下：

The corrections made by Abaqus for shear locking and hourglass control are as follows:

	单元类型 Element Type	元素 Element	修正情况 Correction
剪切自锁 Shear locking	S4	薄膜刚度 Thin Film Stiffness	假设应变方法修正 Correction of Assumed Strain Method
		面外弯曲刚度 Out-of-plane bending stiffness	无
		面外横向剪切刚度 Out-of-plane shear stiffness	假设应变方法修正 Correction of Assumed Strain Method
	S4R	所有项 All Items	无
沙漏控制 Sandglass Control	S4	薄膜刚度 Film Stiffness	无
		面外弯曲刚度 Out-of-plane bending stiffness	无
		面外横向剪切刚度 Out-of-plane shear stiffness	沙漏控制，和Belytchko公式不一致，暂时没研究 Sandglass Control, inconsistent with Belytchko formula, not studied yet
	S4R	薄膜刚度 Film Stiffness	和Belytchko公式一致，因子取0.005G Consistent with the Belytchko formula, the factor is taken as 0.005G
		面外弯曲刚度 Out-of-plane bending stiffness	和Belytchko公式一致，因子取0.00375G*4 Consistent with the Belytchko formula, the factor is taken as 0.00375G*4
		面外横向剪切刚度 Out-of-plane shear stiffness	沙漏控制，和Belytchko公式不一致，暂时没研究 Sandglass control, inconsistent with the Belytchko formula, not yet researched

详细研究方法，见附件： Detailed research methods, see attachment:

有限元理论基础及Abaqus内部实现方式研究系列3：S4壳单元剪切自锁和沙漏控制(SnowWave02_20171018).pdf

Fundamental Theory of Finite Element Method and Research on Internal Implementation of Abaqus Series 3: Shear Locking and Lysimeter Control of S4 Shell Element (SnowWave02_20171018).pdf

推荐阅读 Recommended Reading

Abaqus、iSolver与Nastran梁单元差异...

SnowWave02 免费 Free

转子旋转的周期性模型-水冷电机散热仿真 Periodic Model of Rotor...

技术邻小李 Technical Neighbor Xiao Li ¥100 100 Yuan

非局部均值滤波和MATLAB程序详解视频算法及其保留图形细节应用...

正一算法程序 Zhengyi Algorithm Program ¥220 220 Yuan

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