Ph. D. Thesis Presentation

Partition of Unity Based Shell Finite Elements

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Ocean Systems Engineering, KAIST
Nov. 4th, 2014

Ph. D. Thesis Presentation

Committee

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- Prof. HyukChun Noh (Civil and Environmental Engineering, Sejong University)
- Prof. Hyun Chung (Ocean Systems Engineering, KAIST)
- Prof. YeunWoo Cho (Ocean Systems Engineering, KAIST)
- Prof. Seunghwa Ryu (Mechanical Engineering, KAIST)

Goal

: To develop the efficient and robust shell finite elements based on partition of unity concept.

Limitations :

- Linear and nonlinear static analyses
- Shell elements with the effects shear deformation (Reissner-Mindlin theory)

Contents : Partition of unity based shell finite elements

1. Part I (Introduction to Partition of Unity (PU) Based FEM)
   - Brief History of the Finite Element Method
   - Application of the Finite Element Method
   - Finite Element Analysis Procedures
   - Ultimate Goal of the Finite Element Method
   - Partition of Unity Based Shell Finite Element

   → **Enriched MITC3**

2. Part II (PU Based Shell Element with Improved Membrane Behaviors)
   - Introduction to Nonlinear Finite Element Analysis
   - Introduction and Scope of Research
   - **MITC3+ in the Nonlinear Analysis**
     - ✓ Key Concepts / Nonlinear Formulation
     - ✓ Benchmark Problems

     → **MITC3+**
   - **The Method with Improved Membrane Behaviors**
     - Comparison with Other Methods
     - Key Concepts / Nonlinear Formulation
     - Benchmark Problems

   → **Enriched MITC3+**

3. Future Works

4. Conclusions

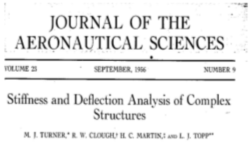
Part I:

Introduction to Partition of Unity (PU) Based FEM

- Brief History of the Finite Element Method
- Application of the Finite Element Method
- Finite Element Analysis Procedures
- Ultimate Goal of the Finite Element Method
- Partition of Unity Based Shell Finite Elements

Events in the Finite Element Methods

1956: First paper by Turner, Clough, Martin and Topp



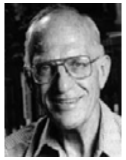
JOURNAL OF THE AERONAUTICAL SCIENCES

VOLUME 23 SEPTEMBER, 1956 NUMBER 9

Stiffness and Deflection Analysis of Complex Structures

M. J. TURNER, R. W. CLOUGH, H. C. MARTIN, and L. J. TOPP

1960: FEM coined by Clough

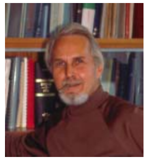


UC Berkely 1950

1971: First FEAP by Taylor

1970s: Commercial software (ABAQUS, ANSYS, ADINA)

1971: Reduced integration by Zienkiewicz



1990: EAS by Simo

1999: XFEM by Belytschko

1960 — 1970 — 1980 — 1990 — 2000 — 2010

~1960
- Direct Stiffness Method
- Force Method

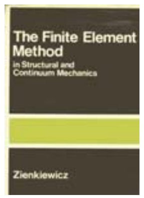
1958: UC program using IBM 704 by Wilson

1962: Isoparametric element by Taig

1966: Numerical integration by Irons

1970: Curved shell by Ahmad

1967: First book by Zienkiewicz



1976: Incompatible mode by Taylor

1982: ANS by MacNeal

1984: MITC by Bathe

2000: GFEM (PU FEM) by Strouboulis

2005: IGA by Hughes

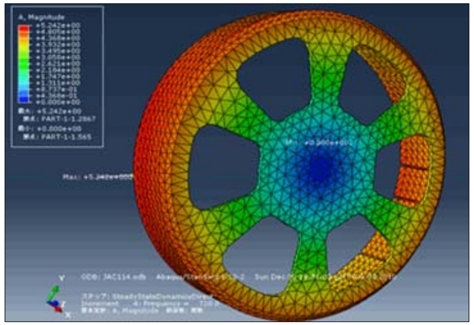
List of finite element software packages – Commercial FEA software

FEA software list

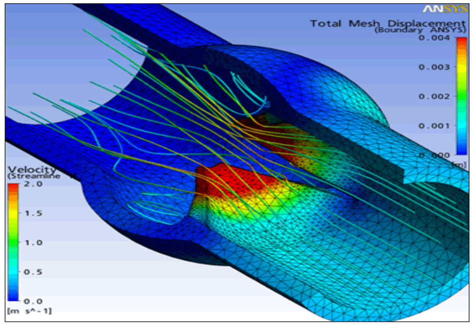
Commercial (48)
ABAQUS
ANSYS
ADINA
NASTRAN
ALGOR
LS-DYNA
PAM-CRASH
MARC
LUSAS
COMSOL
VISUALFEA
FEMAP
……..

Open source (19)
FreeFem++
OOFEM
jFEM
GetFEM++
Code Aster
……..

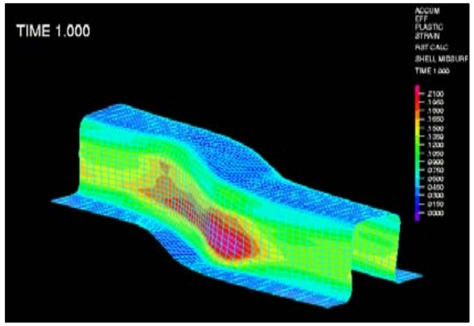
Proprietary / Commercial Finite Element Analysis (FEA) Software



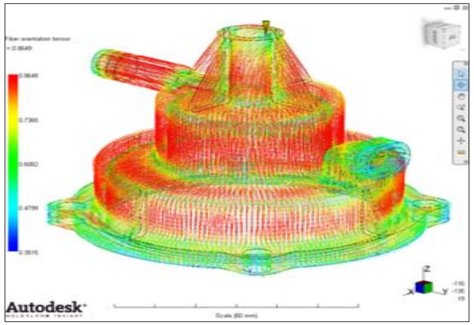
ABAQUS



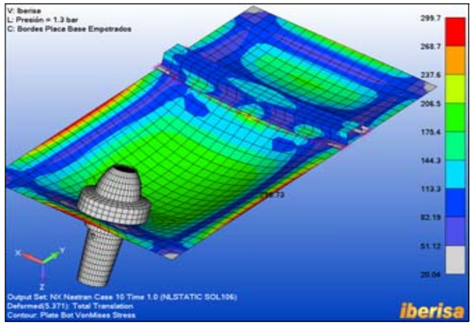
ANSYS



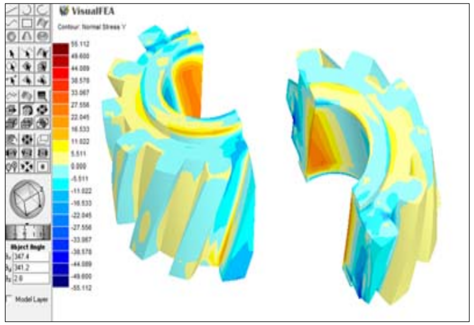
ADINA



ALGOR



NASTRAN

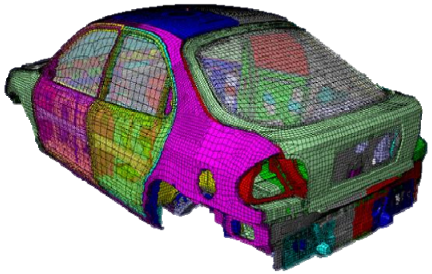


VISUALFEA

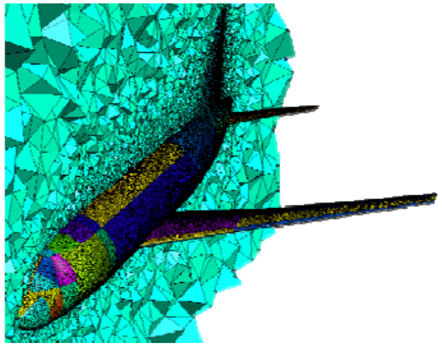
Commercial FEA software prices start from around $1,500 to $60,000.

Figure source : google image

Applications of FEM #1 – Industry fields

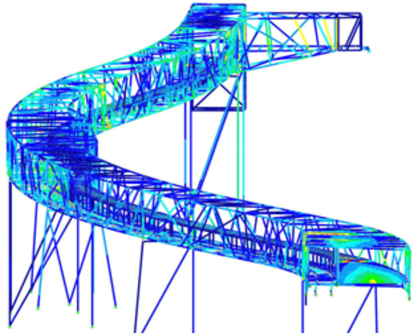


Automobile

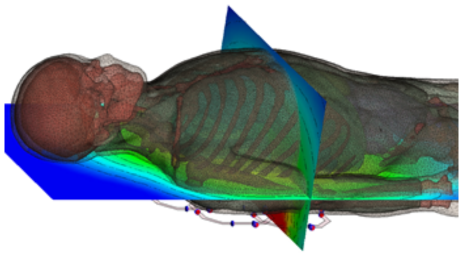


Aerospace

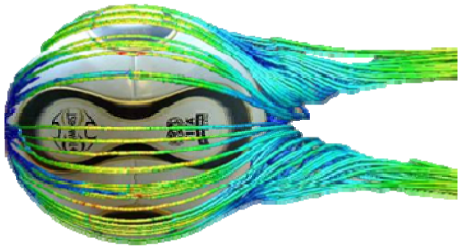
Electronics



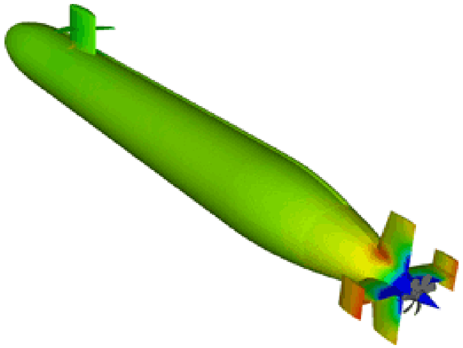
Civil engineering



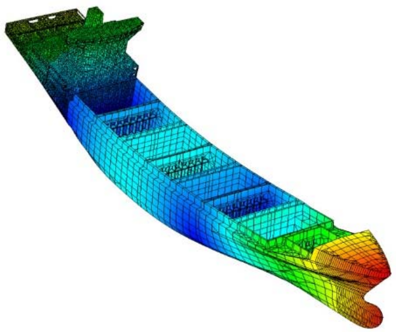
Healthcare



Sports



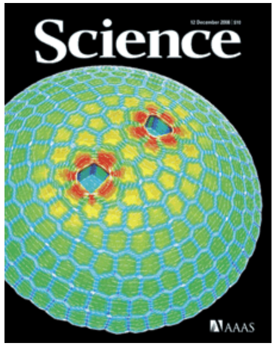
Defense



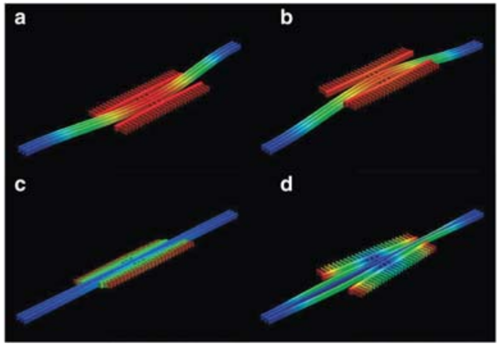
Ship building

Figure source : google image

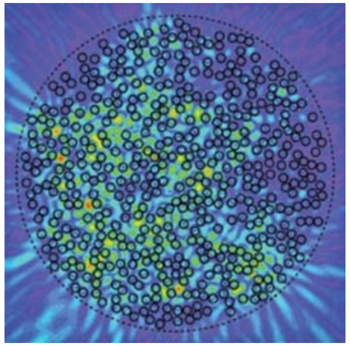
Applications of FEM #2 – Research fields (High profile journal)



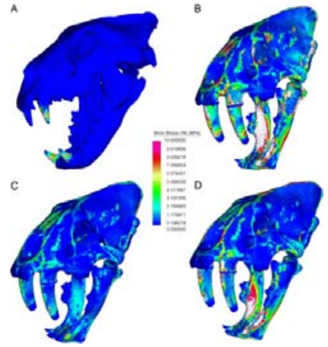
Olivier et al., Science 2008
(Developmental patterning)



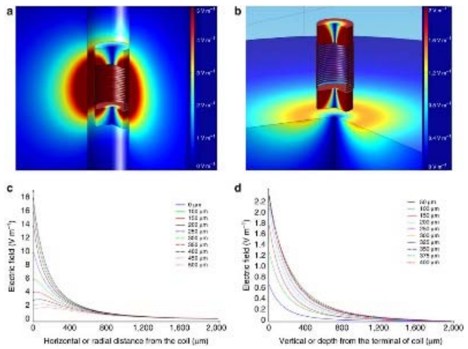
Dario et al., Nature Communications 2011
(Frequency stabilization)



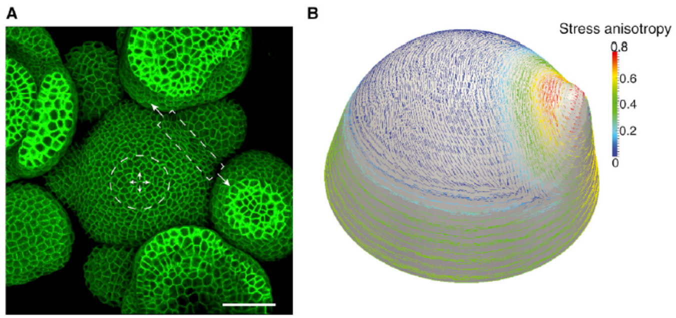
Diederik et al. Nature Photonics 2013
(Disordered photonics)



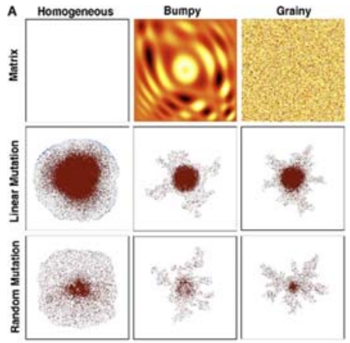
McHenry et al. PNAS 2007
(Predatory behavior in *Smilodon*)



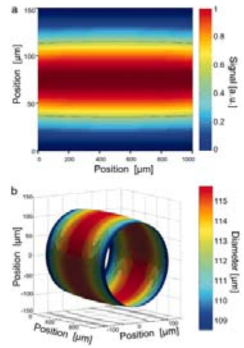
Giorgio et al., Nature Communications 2012
(Microscopic magnetic simulation)



Sampathkumar et al. Cell Current Biology 2014
(Plant development)



Anderson et al. Cell Theory 2006
(Tumor morphology)



Masson et al. PNAS 2006
(Ionic contrast terahertz)

Figure source : journals

Is there nothing left to improve FEMs?

CLUE

- Many researchers and their contributions over 50 years
- More than 10,000,000 papers to improve performance of the FEMs
- Most widely used numerical methods in engineering
- Stabilized commercial software products (e.g. ABQUS, ANSYS, ADINA,…)

ANSWER : Of course, more research is needed despite the remarkable developments and improvements.

Step 1

: Observation of the system

Column under an eccentric compressive load

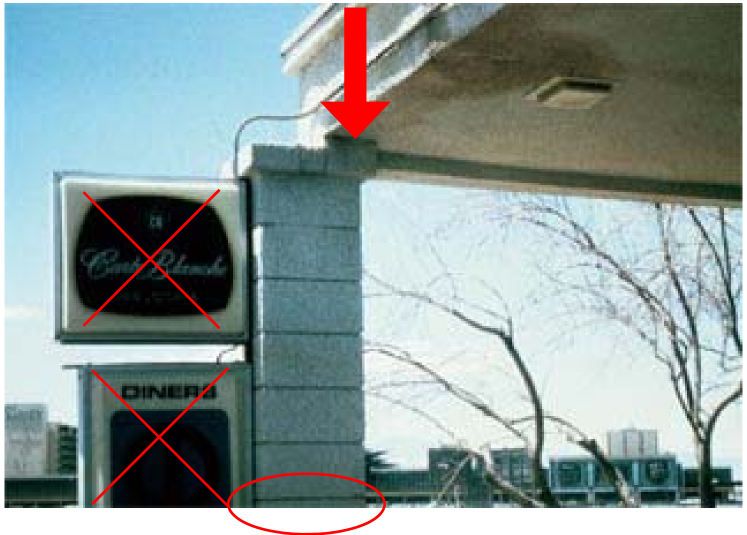
This eccentric load is perpendicular to the column, but it doesn't pass through the column's centroid.

Figure source : google image

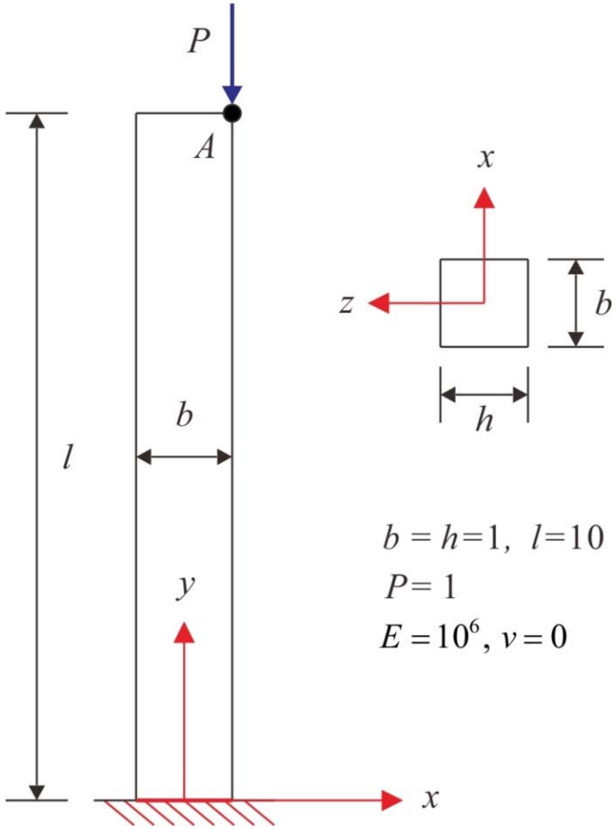
Step 2
: Idealization of the system

Major assumption : Linear elastic material

Appling an eccentric load



Idealization



Imposing the boundary condition

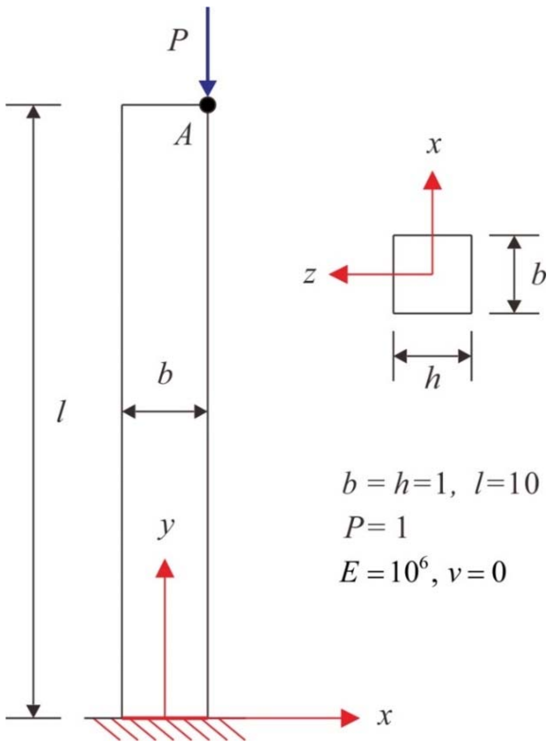
See the dissertation, p. 121

Step 3

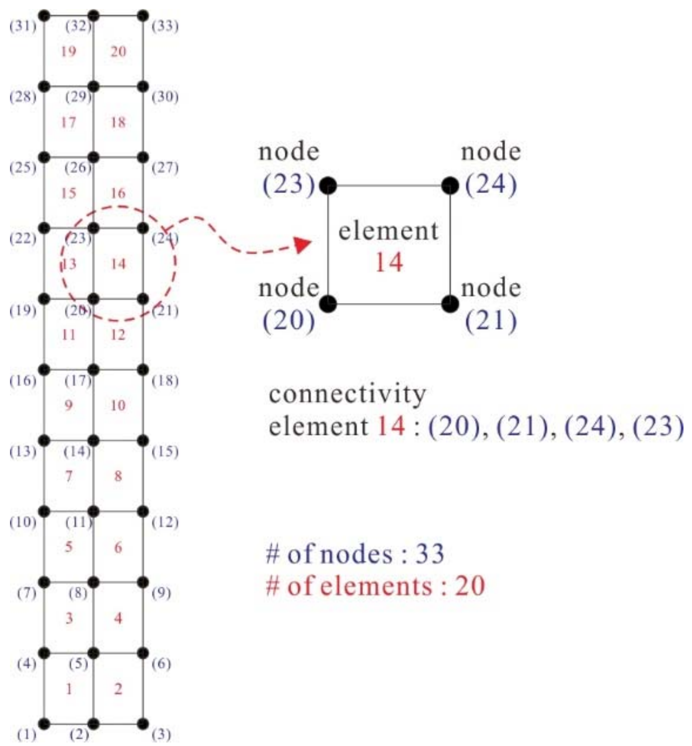
: Discretization of the domain

(using ADINA founded in 1974, ADINA 9.0.5 latest released version (2014.10))

(setting the material properties, imposing the boundary condition, and applying loads)



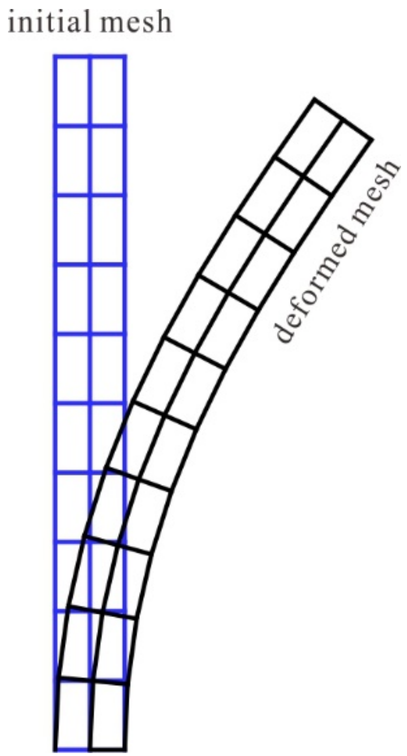
FE discretization



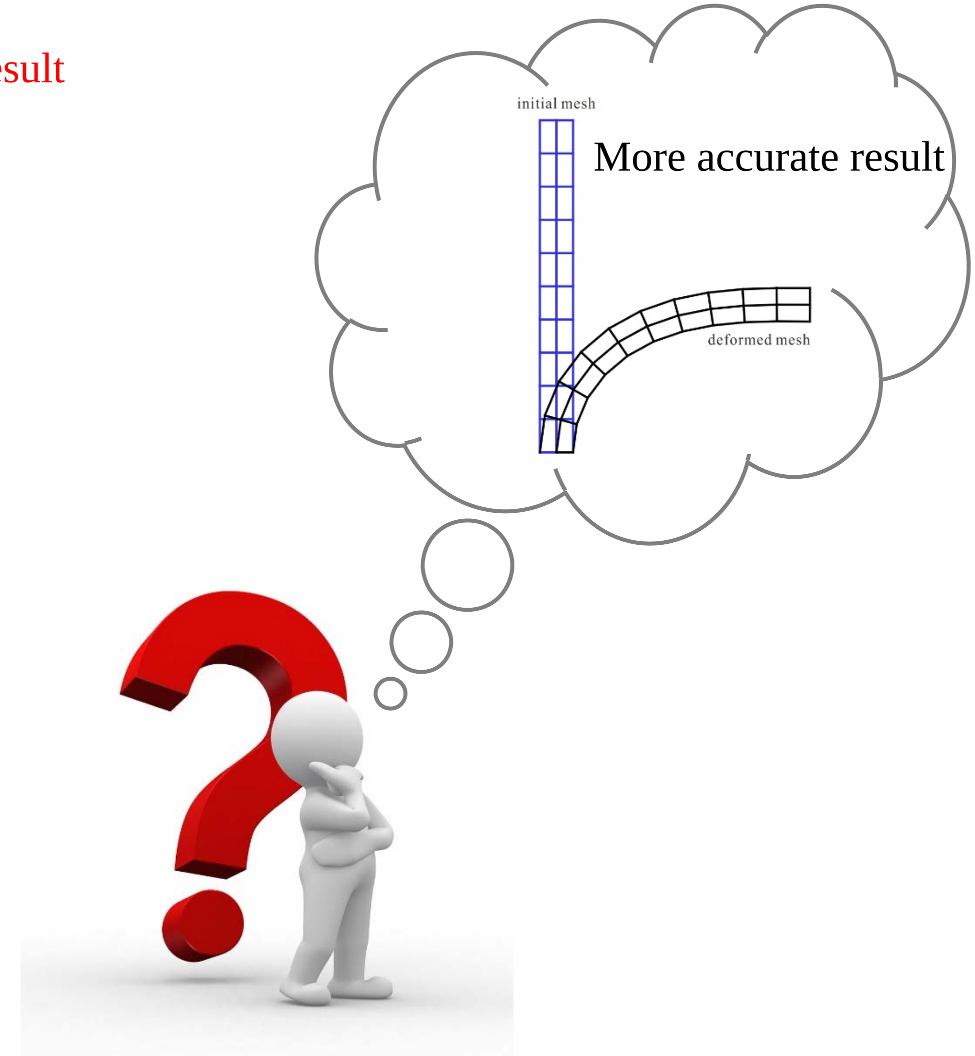
FE analysis procedures – Step 4: Solving the problem and interpreting the result

Step 4

: Solving the problem and interpreting the result

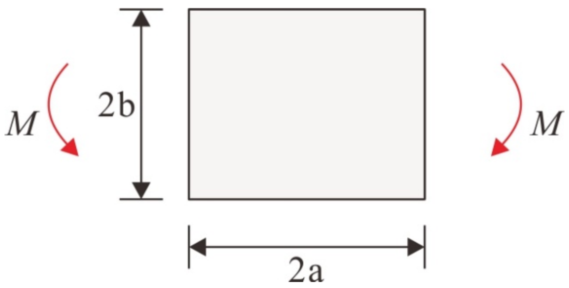


Result : deformed shape of the column

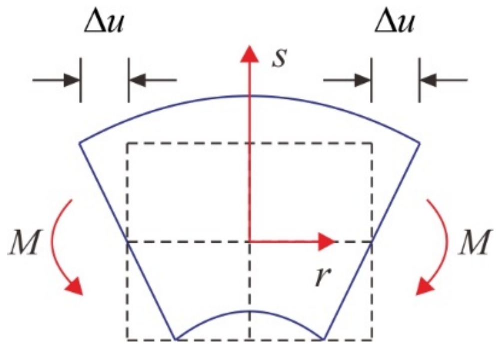


See the dissertation, p. 122

2D pure bending problem



Correct beam deformation

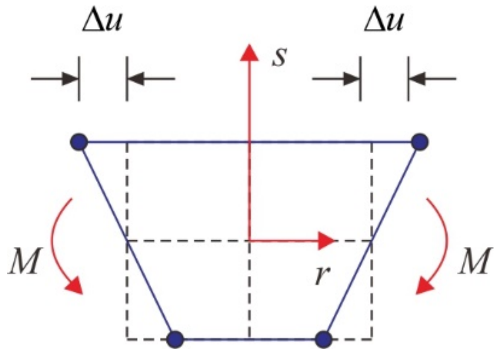


$$u(r,s) = \frac{M}{EI} rs$$

$$v(r,s) = \frac{Ma^2}{2EI}\left(1 - \frac{r^2}{a^2}\right) + \frac{Mb^2}{2EI}\left(1 - \frac{s^2}{b^2}\right)$$

$$\gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} = 0$$

Finite element deformation



$$u(r,s) = \Delta urs$$

$$v = 0$$

$$\gamma_{xy} = \Delta ur$$

Parasitic in-plane shear strain

In-plane shear locking : The element has an excess of shear strain which contributes to the poor ability of the element to reproduce bending modes.

See the dissertation, p. 7

Remedies – Books and manual books

Amazon search
450 results in science & math, keyword : “finite element method”

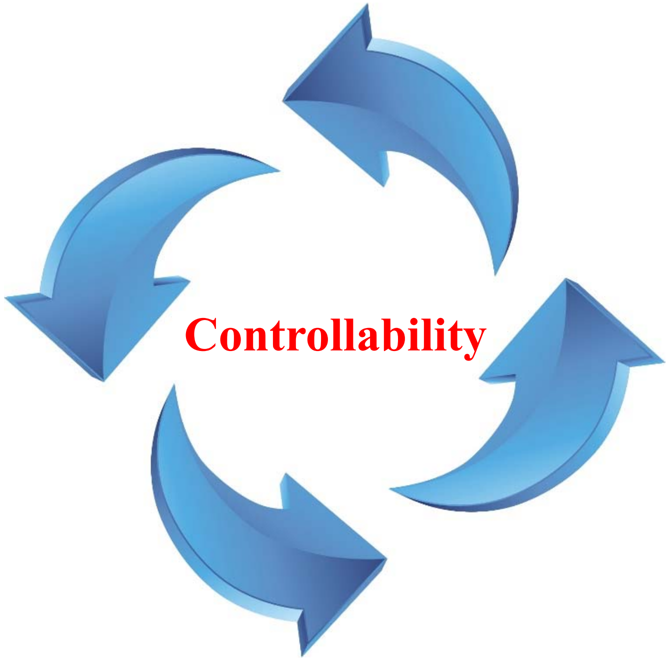
Commercial software : ADINA
Manual book : 12 books

The ultimate goal of the finite element method #1 – User conveniences & Accuracy

Accurate solution & **User conveniences**

What does "user conveniences" mean?

One click



Reliable results

The ultimate goal of the finite element method #2 – User conveniences & Accuracy

General procedure

Step 1: Observation of the system

↓

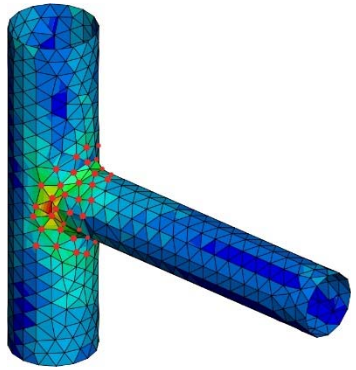
Step 2: Idealization of the system

↓

Step 3: Discretization of the domain

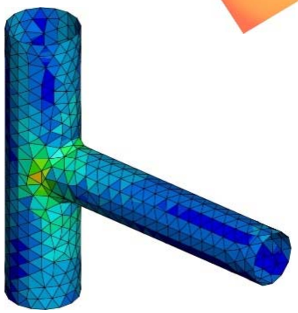
↓

Step 4: Solving the problem

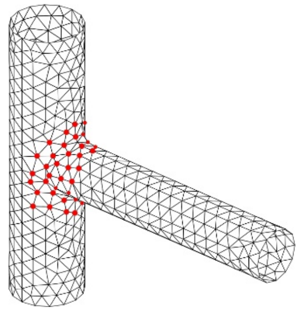


Accurate solution

Additional procedure



Estimating the FE errors



Locally enrichment without mesh refinements

See the dissertation, p. 50

The ultimate goal of the finite element method #3 – Error estimates

"A Finite element solution contains enough information to estimate its own error"

Cook RD et al., Concepts and applications of finite element analysis, 4th ed., Wiley.

"Nowadays, a booming activity in error estimation is fostered by better understanding of mathematical foundations"

Aninsworth M, Oden JT, A posteriori error estimation in finite element analysis, Wiley

Two types of error estimates serve very different purpose

- A priori error estimates
  - To check the order of convergence of a given FE method

- **A posteriori error estimates**
  - To indicate where the error is particularly high

I. Residuals – based method

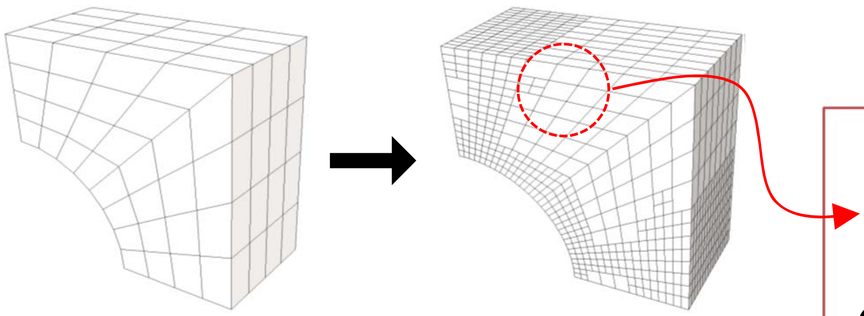
Babuska I and Rheinboldt WC, Int. J. Numer. Meth. Eng.;12:1597-615, 1978 (1371 cited)

II. Recovery – based method

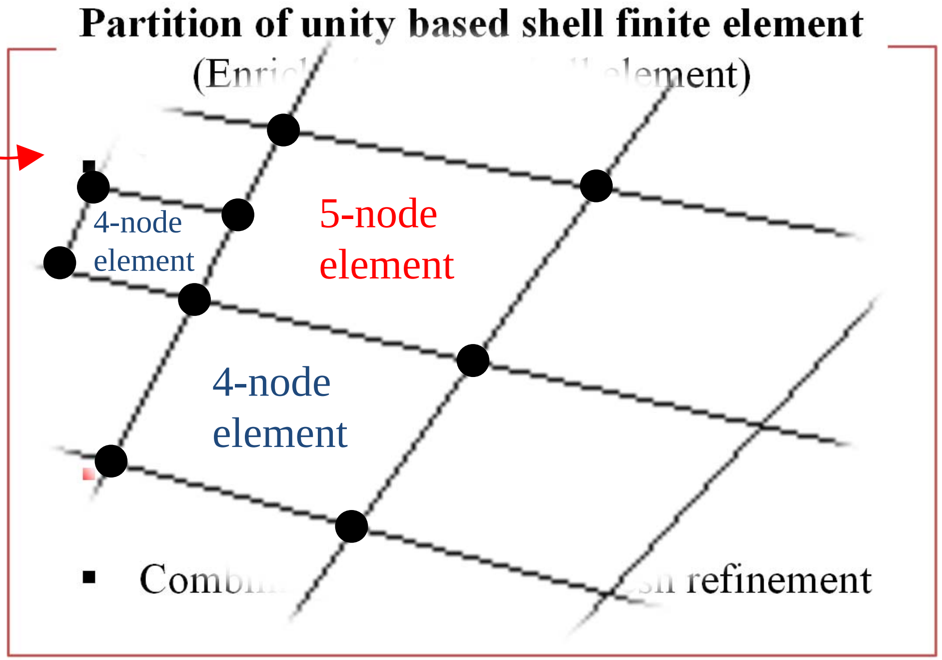
Zienkiewiz OC and Zhu JZ, Int. J. Numer. Meth. Eng.;24:337-57,1987 – ZZ method (2147 cited)

The ultimate goal of the finite element method #4 – Error estimates

Error estimate / Adaptive mesh refinement



Hyang et al., DDMSE;78:53-74,2011



Disadvantages

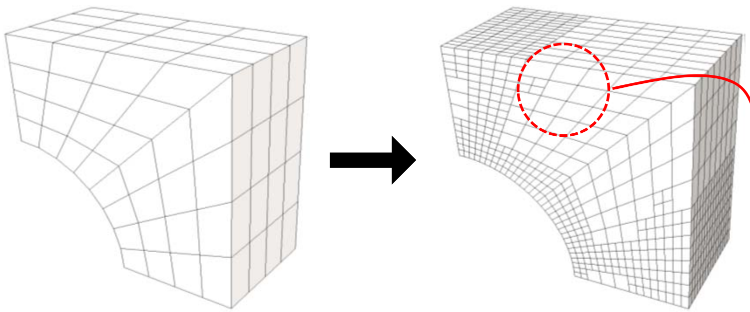
- Mesh refinement algorithms
- Only *h*-refinement
- 2D / 3D solid problem
- Transition elements

If shell problem,
how can treat the locking phenomenon?

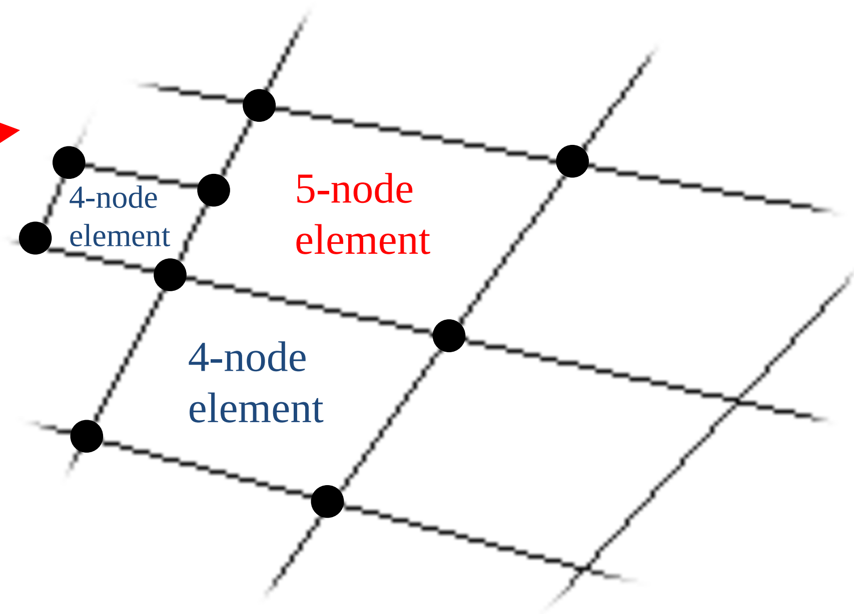
See the dissertation, p. 24

The ultimate goal of the finite element method #4 – Error estimates

Error estimate / Adaptive mesh refinement



Hyang et al., DDMSE;78:53-74,2011



Disadvantages

- Mesh refinement algorithms
- Only *h*-refinement
- 2D / 3D solid problem
- Transition elements

If shell problem,
how can treat the locking phenomenon?

See the dissertation, p. 24

FEM $u(\mathbf{x}) = \sum_{i=1}^{3} h_i u_i$

PU based FEM $\bar{u}(\mathbf{x}) = \sum_{i=1}^{3} h_i u_i(\mathbf{x})$

- h_i : shape function
- u_i : nodal displacement **variable**
- $u_i(\mathbf{x})$: local approximation **function**

Local approximation , $u_i(\mathbf{x})$

$$u_i(\mathbf{x}) = \mathbf{p}^{\mathrm{T}}\mathbf{a}(\mathbf{x}) \qquad \mathbf{p}^{\mathrm{T}}(\mathbf{x}) = [1,\ x,\ y,\ xy,\ \ldots]$$

$$\mathbf{a}(\mathbf{x}) = [a_{1i},\ a_{2i},\ a_{3i},\ a_{4i},\ \ldots]$$

$$u_i(\mathbf{x}) = a_{1i} + x a_{2i} + y a_{3i}$$

$$u_i(x_i, y_i) = a_{1i} + x_i a_{2i} + y_i a_{3i} = u_i$$

$$a_{1i} = u_i - x_i a_{2i} - y_i a_{3i}$$

$$u_i(\mathbf{x}) = u_i + (x - x_i)a_{2i} + (y - y_i)a_{3i}$$

$$\bar{u}(\mathbf{x}) = \sum_{i=1}^{3} h_i u_i(\mathbf{x})$$

$$= \sum_{i=1}^{3} h_i \left[u_i + (x - x_i)a_{2i} + (y - y_i)a_{3i}\right]$$

$$= \sum_{i=1}^{3} h_i u_i + \sum_{i=1}^{3} h_i (x - x_i)a_{2i} + h_i (y - y_i)a_{3i}$$

$$= u + \hat{u}$$

- Use of the high order interpolation
- Local use

See the dissertation, p. 26

PU based MITC3 shell element – Locking treatment

The linear terms of the enriched covariant strain components

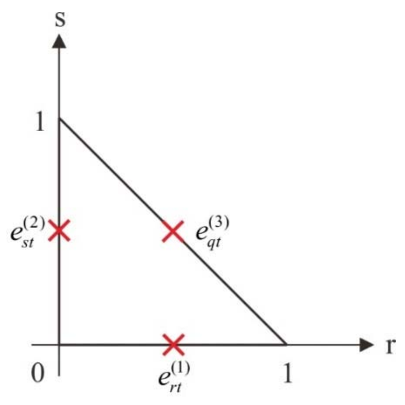
$$\bar{\mathbf{g}}_i = \frac{\partial(\mathbf{x}+\hat{\mathbf{x}})}{\partial r_i} = \frac{\partial \mathbf{x}}{\partial r_i} = \mathbf{g}_i$$

$$\bar{e}_{ij} = \frac{1}{2}\left(\bar{\mathbf{g}}_i \cdot \bar{\mathbf{u}}_{,j} + \bar{\mathbf{g}}_j \cdot \bar{\mathbf{u}}_{,i}\right)$$

$$\bar{e}_{ij} = \frac{1}{2}\left(\mathbf{g}_i \cdot \mathbf{u}_{,j} + \mathbf{g}_j \cdot \mathbf{u}_{,i}\right) + \frac{1}{2}\left(\mathbf{g}_i \cdot \hat{\mathbf{u}}_{,j} + \mathbf{g}_j \cdot \hat{\mathbf{u}}_{,i}\right)$$

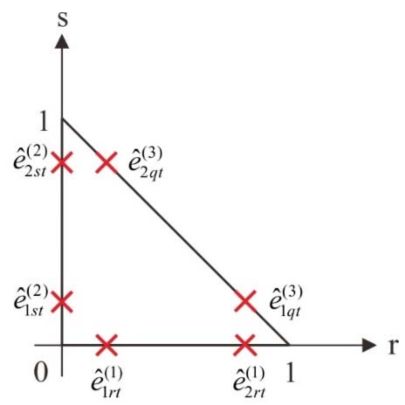
PU based MITC3 shell element (also called enriched MITC3)

MITC3



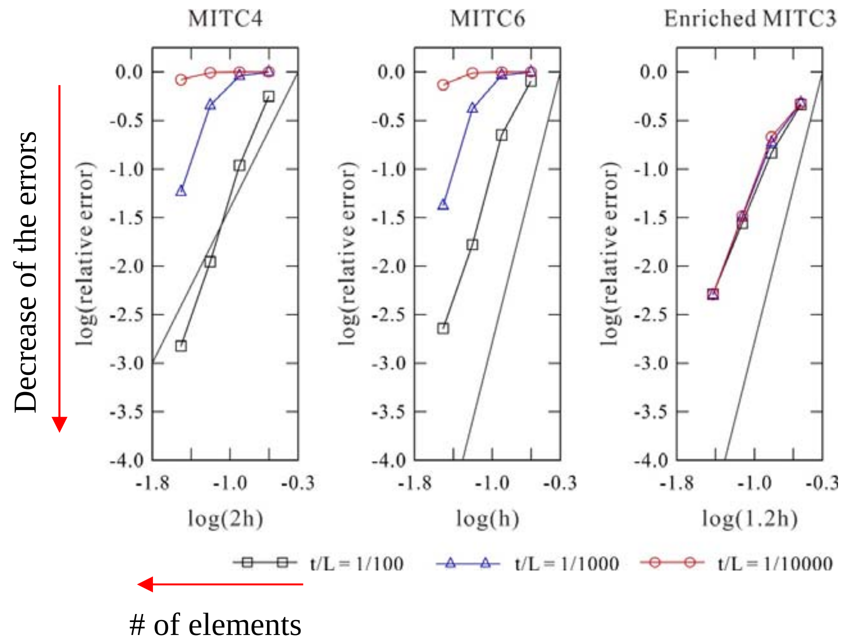
$$\tilde{e}_{rt} = a_1 + cs$$
$$\tilde{e}_{st} = a_2 - cr$$

MITC6



$$\tilde{e}_{rt} = a_1 + b_1 r + c_1 s$$
$$\tilde{e}_{st} = a_2 + b_2 r + c_2 s$$

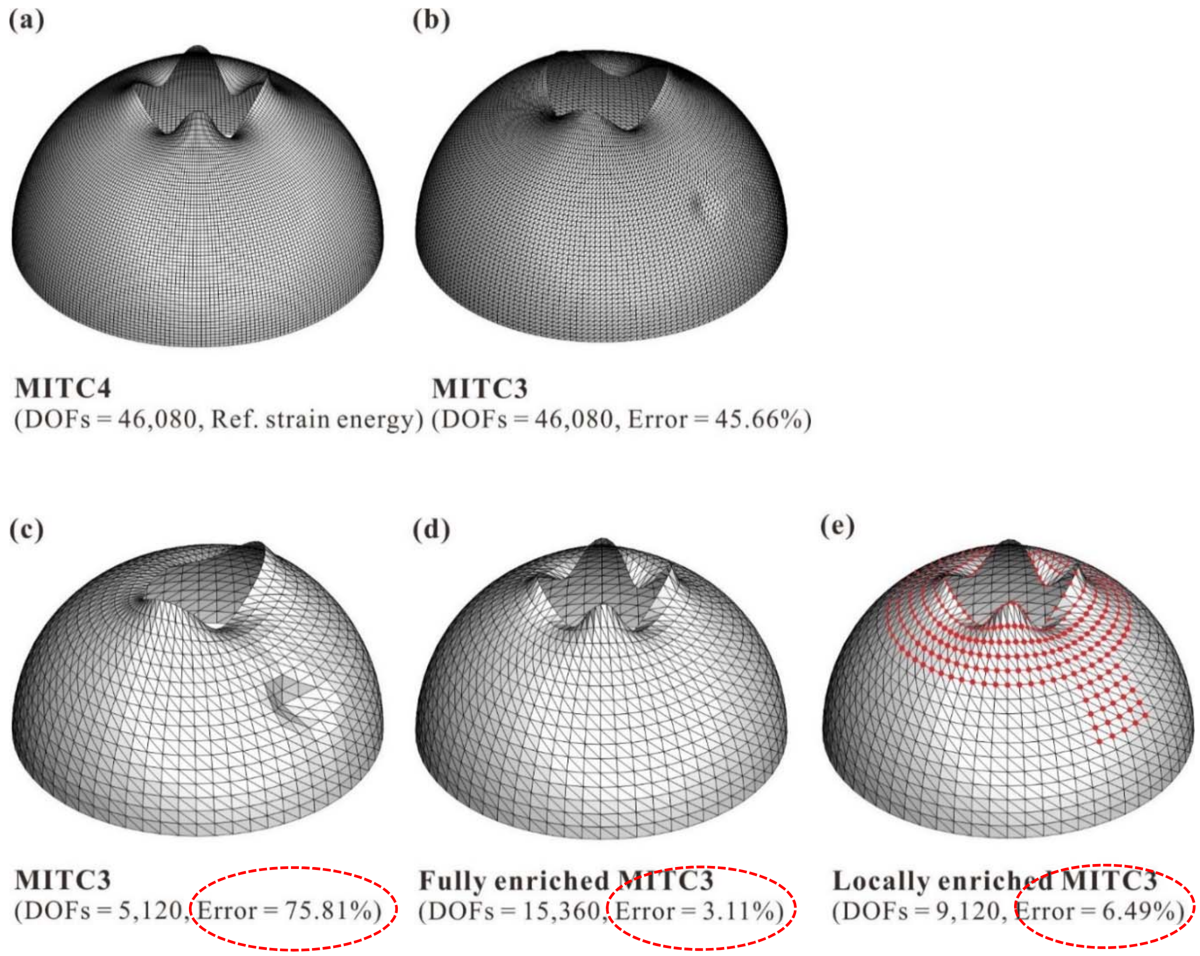
Convergence study



PU based MITC3 shell element – “Highly sensitive” shell problem

Fine mesh

Coarse mesh



Jeon HM, Lee PS, Bathe KJ. *The MITC3 shell finite element enriched by interpolation covers. Comput Struct 2014;134:128-42.*

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The MITC3 shell finite element enriched by interpolation covers

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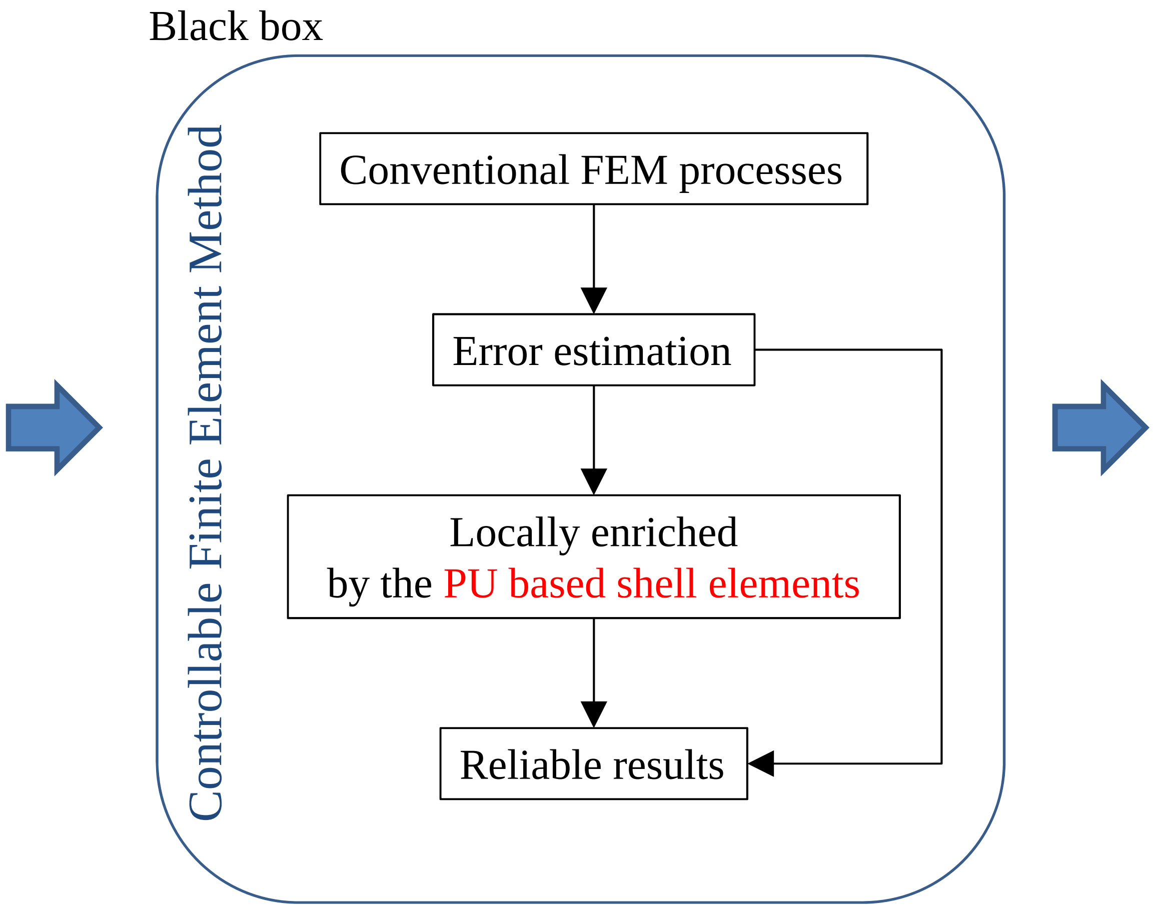
ABSTRACT

In this paper, we develop a scheme to enrich the 3-node triangular MITC shell finite element by interpolation cover functions. The MITC method is used for the standard and enriched displacement interpolations. The enriched 3-node shell finite element not only captures higher gradients but also decreases inter-elemental stress jumps. In particular, the enrichment scheme increases the solution accuracy without any traditional local mesh refinement. Convergence studies considering a fully clamped square plate problem, cylindrical shell problems, and hyperboloid shell problems demonstrate the good predictive capability of the enriched MITC3 shell finite element, even when distorted meshes are used. We evaluate the effectiveness of the method, and also illustrate the use of the enrichment scheme applied only locally through the solution of two additional shell problems: a shaft–shaft interaction problem and a monster shell problem.

The ultimate goal of the FEMs – PU based shell finite elements

Biologist
Engineer
Chemistry



Analysis of nan
Biological pher
Engineering str

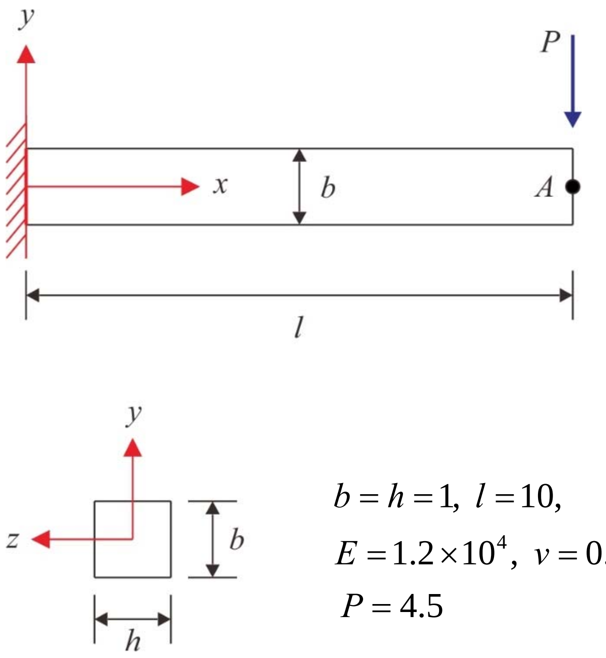
Part II:

PU based Shell Element with Improved Membrane Response)

- Introduction to Nonlinear Finite Element Analysis
- Introduction and Scope of Research
- **MITC3+ Shell Element in the Nonlinear Analysis**
  - Key Concepts / Nonlinear Formulation
  - Benchmark Problems
- **The Method with Improved Membrane Behaviors**
  - Comparison with Other Methods
  - Key Concepts / Nonlinear Formulation
  - Benchmark Problems

Classification
- Geometric nonlinear analysis
- Material nonlinear analysis
- Changing in boundary condition

Cantilever beam subjected to end shear force



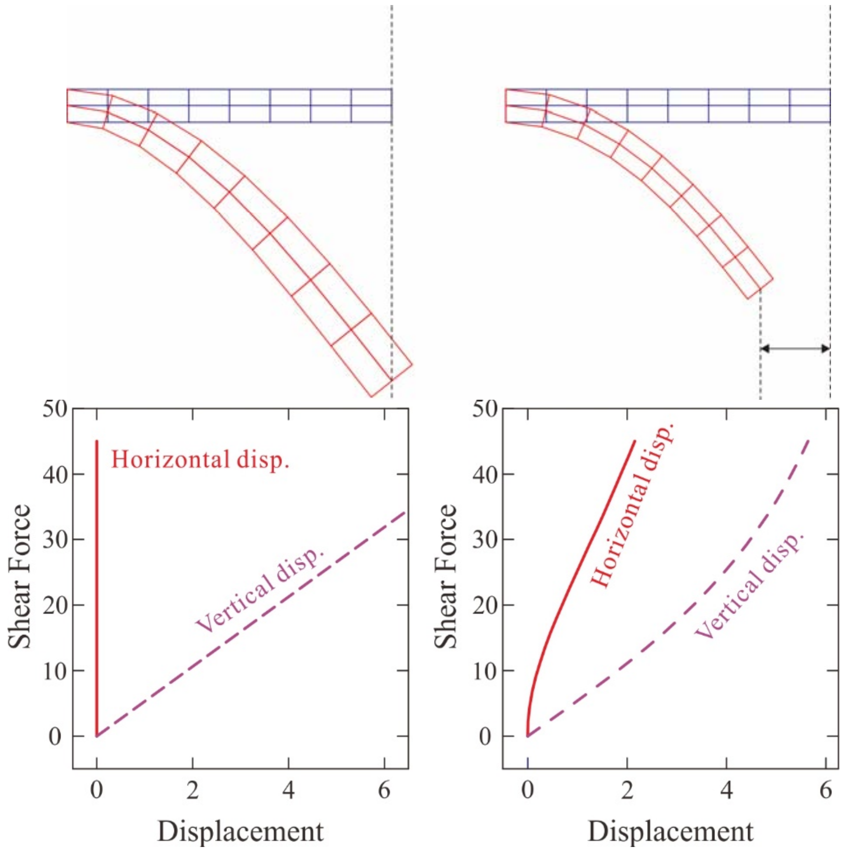
$b = h = 1,\ l = 10,$

$E = 1.2 \times 10^4,\ \nu = 0.3$

$P = 4.5$

Linear analysis

Nonlinear analysis



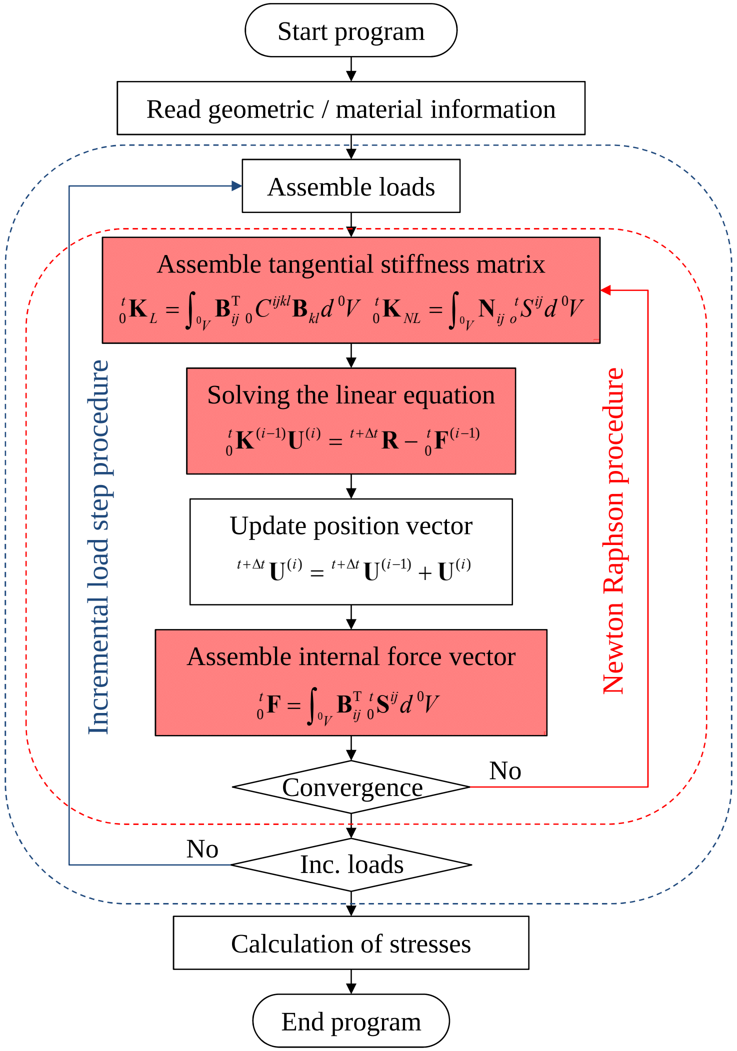
	LINEAR ANALYSIS	NONLINEAR ANALYSIS
1. Strain	Infinitesimal strain $e_{ij}=\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)$	Green-Lagrange strain $e_{ij}=\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}+\frac{\partial u_k}{\partial x_i}\cdot\frac{\partial u_k}{\partial x_j}\right)$
2. Rotation (curved beam/shell)	Infinitesimal rotation ${}^{t+\Delta t}\mathbf{V}_n^i={}^{t+\Delta t}_{\ t}\mathbf{Q}^i\,{}^t\mathbf{V}_n^i$ ${}^{t+\Delta t}_{\ t}\mathbf{Q}^i=\mathbf{I}_3+{}^{t+\Delta t}_{\ t}\mathbf{\Theta}^i$ ${}^{t+\Delta t}_{\ t}\mathbf{\Theta}^i=\begin{bmatrix}0 & -{}^{t+\Delta t}_{\ t}\theta_3^i & {}^{t+\Delta t}_{\ t}\theta_2^i\\ {}^{t+\Delta t}_{\ t}\theta_3^i & 0 & -{}^{t+\Delta t}_{\ t}\theta_1^i\\ -{}^{t+\Delta t}_{\ t}\theta_2^i & {}^{t+\Delta t}_{\ t}\theta_1^i & 0\end{bmatrix}$ ▶ $-\mathbf{V}_2^i\alpha_i+\mathbf{V}_1^i\beta_i$	Finite rotation ${}^{t+\Delta t}\mathbf{V}_n^i={}^{t+\Delta t}_{\ t}\mathbf{Q}^i\,{}^t\mathbf{V}_n^i$ ${}^{t+\Delta t}_{\ t}\mathbf{Q}^i=\mathbf{I}_3+{}^{t+\Delta t}_{\ t}\mathbf{\Theta}^i+\frac{1}{2!}({}^{t+\Delta t}_{\ t}\mathbf{\Theta}^i)^2$ ${}^{t+\Delta t}_{\ t}\mathbf{\Theta}^i=\begin{bmatrix}0 & -{}^{t+\Delta t}_{\ t}\theta_3^i & {}^{t+\Delta t}_{\ t}\theta_2^i\\ {}^{t+\Delta t}_{\ t}\theta_3^i & 0 & -{}^{t+\Delta t}_{\ t}\theta_1^i\\ -{}^{t+\Delta t}_{\ t}\theta_2^i & {}^{t+\Delta t}_{\ t}\theta_1^i & 0\end{bmatrix}$ ▶ $-\alpha_i\,{}^t\mathbf{V}_2^i+\beta_i\,{}^t\mathbf{V}_1^i-\frac{1}{2}(\alpha_i^2+\beta_i^2)\,{}^t\mathbf{V}_n^i$
3. Framework	-	◇ Total Lagrangian formulation ◇ Update Lagrangian formulation ◇ Corotational formulation
4. Iterative scheme	-	○ Full Newton-Raphson method ○ Modified Newton-Raphson method ○ BFGS matrix update method

Three types of approaches

: to improve the nonlinear finite element solution

1. Using the **high performance computing**
2. Obtaining the **Equilibrium path**
3. Development and improvement of the **finite elements** (present research)

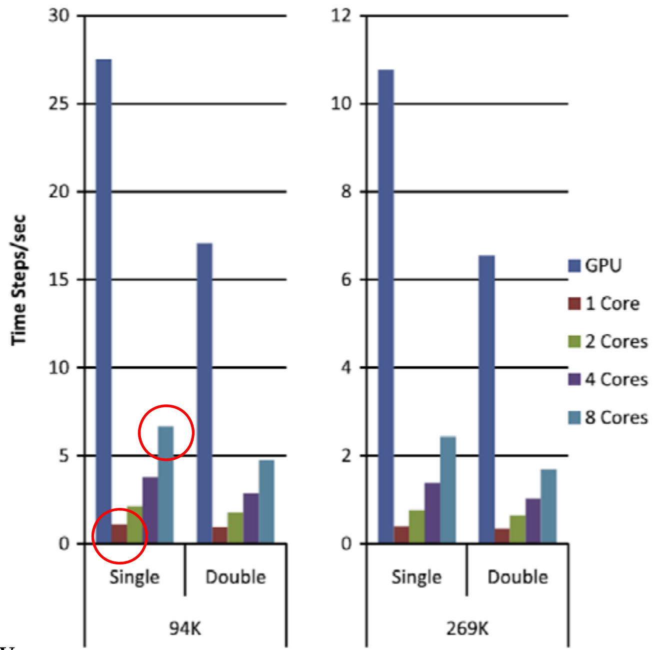
Geometric nonlinear FE procedure



High performance computing

Two quad core Intel Xeon X5560
Core : 8 running at 3.2 GHz
RAM : 48 GB of DDR31333MHz
Parallel library : OpenMP

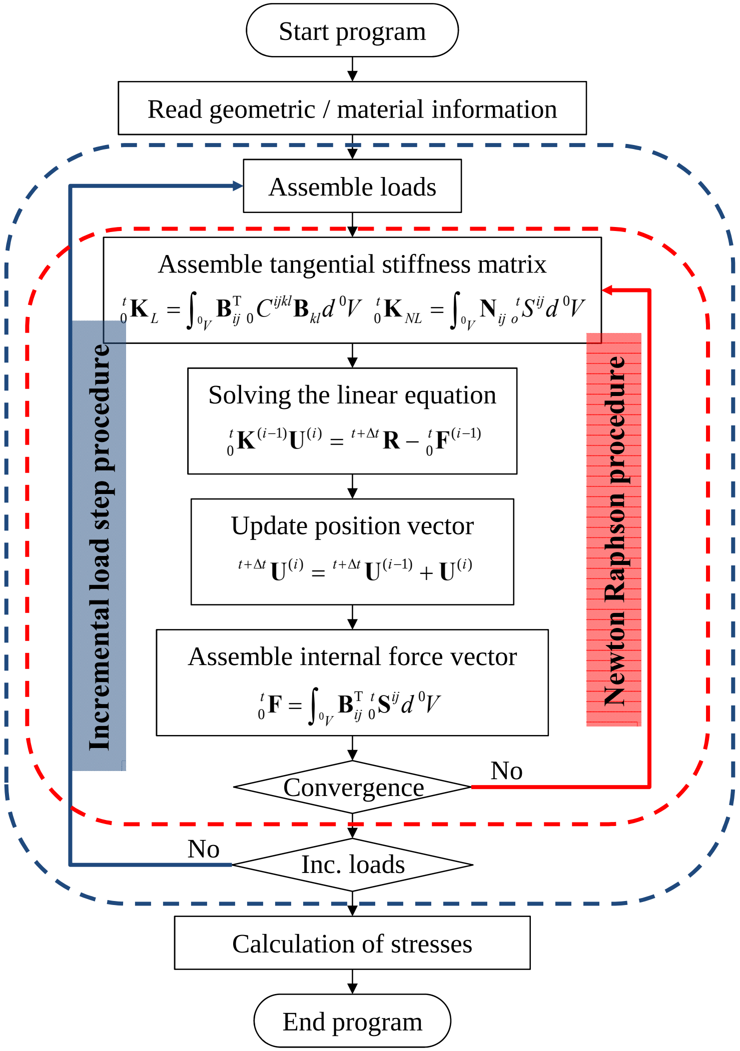
NVIDIA GeForce GTX480
Core : 480 CUDA, 1401 MHz
RAM : 1.5 GB of video memory
Parallel library : CUDA



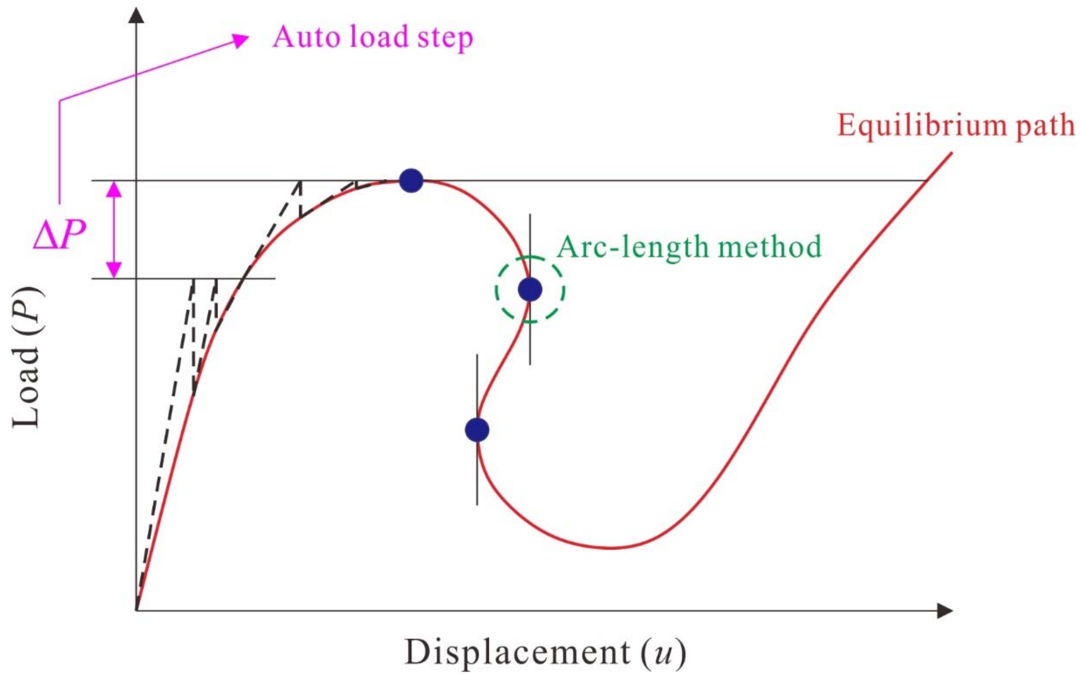
Dick et al., Simul Model Pract Th 2011;19:801-16.
Karatarakis et al., Comput Methods Appl Mech Engrg 2014;269:334-55.

Three types of approaches #2 – Obtaining the equilibrium path

Geometric nonlinear FE procedure

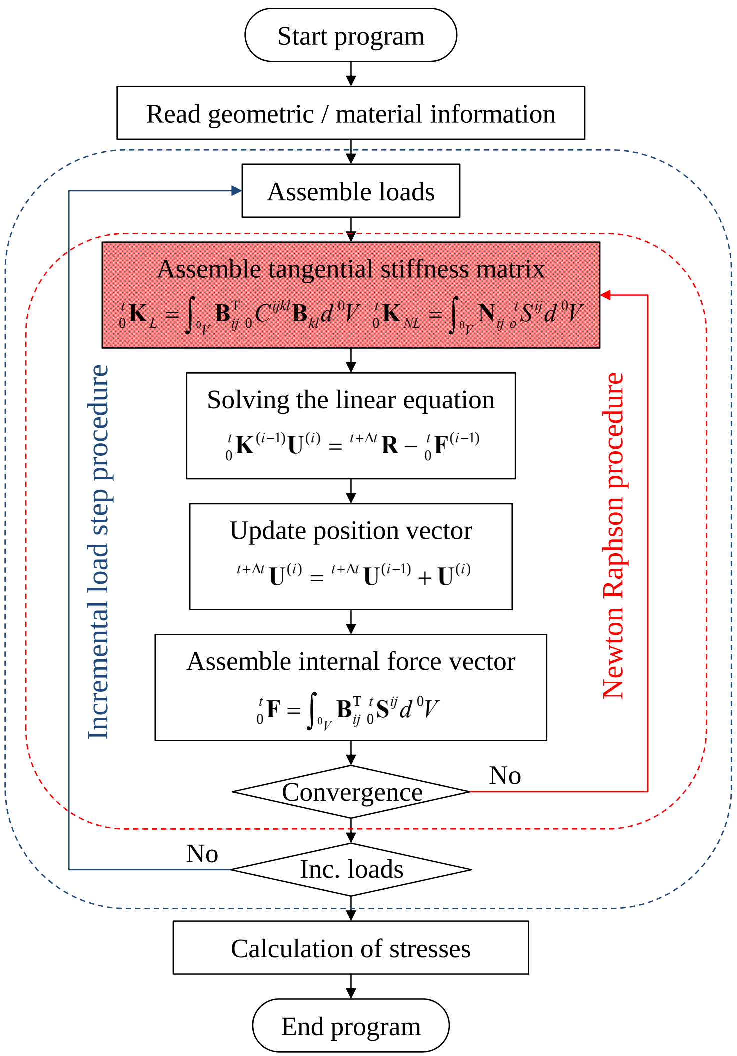


Obtaining the equilibrium path



- Load control / Displacement control (Batoz and Dhatt, 1979)
- Limit point analysis – Arc length method (Riks(1972), Crisfiled(1980))
- Others – Automatic load step(Ramm, 1982), Line search(Box 1969)

Geometric nonlinear FE procedure



Different types of shell elements in commercial software

ABAQUS

S3, S3R, S4, S4R, SAX1, SAX2, SAX2T, SAXA1n, SAXA2n, STRI3, S4R5, STRI65, S8R, S8RT, S8R5, S9R5

ANSYS

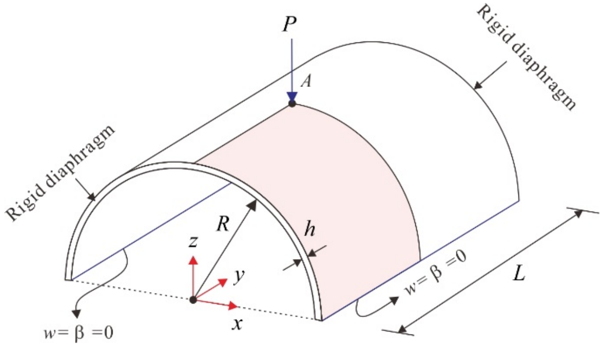
SHELL28, SHELL41, SHELL43, SHELL51, SHELL57, SHELL61 SHELL63, SHELL91, SHELL93, SHELL99, SHELL143, SHELL150 SHELL157, SHELL163, SHELL181, SHELL185

ADINA

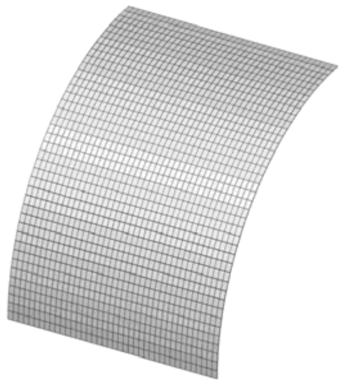
Axisymmetric shell, DISP10 Collapsed
MITC3, MITC4, MITC4i, MITC6, MITC8, MITC9, MITC16

MSC Nastran™

QUAD4, QUAD8, QUADR, TRIA3, TRIA6, TRIAR, TRIA, CONEAX, RTRPLT



- **MITC4 shell element**
- Full Newton-Raphson method
- 100 load step



Deformed shapes
- CODE (C++)
- TECPLOT / PARAVIEW

Commercial software (ADINA)

```
1PROGRAM ADINA - VERSION 8.8.0 (build 01.26.2012)    *** NO HEADING DEFINED ***

 P R I N T   O U T   F O R   T I M E   ( L O A D )   S T E P      100      ( TIME STEP= 0.10C
 DIAG ELEMENT (WITH MAX ABS VALUE) OF THE FACTORIZED MATRIX =    0.77405E+05     NODE =
 DIAG ELEMENT (WITH MIN ABS VALUE) OF THE FACTORIZED MATRIX =    0.21405E+03     NODE =      4

 I N T E R M E D I A T E   P R I N T O U T   D U R I N G   E Q U I L I B R I U M   I T E R A T

          OUT-OF-        NORM OF                                              CONVERGENCE RATIOS  CON
          BALANCE     OUT-OF-BALANCE          NORM OF INCREMENTAL             FOR OUT-OF-BALANCE   F
          ENERGY       FORCE     MOMENT        DISP.      ROTN.     CFORCE       ENERGY      FORCE
                     NODE-DOF   NODE-DOF    NODE-DOF   NODE-DOF    CFNORM                  MOMENT
                    MAX VALUE  MAX VALUE   MAX VALUE  MAX VALUE
                                                                              COMPARE WITH
                                                                             ETOL       RTOL
                                                                           1.00E-03 (NOT USED)(

 ITE=  0  5.35E+00  3.00E+01   8.18E-06    6.31E+00   2.40E-01   0.00E+00    1.00E+00  1.00E+00
                         1-Z       77-Y        34-Z       36-Y   0.00E+00              2.73E-05
                   -3.00E+01  -4.76E-06   -2.58E-01  -7.38E-02

 ITE=  1  3.23E+00  2.80E+02   3.02E+01    2.20E-01   1.23E-02   0.00E+00    6.04E-01  1.00E+00
                        77-X      117-Y        35-Z       36-Y   0.00E+00              5.28E+00
                   -1.02E+02   1.18E+01   -1.73E-02  -5.49E-03

 ITE=  2  2.94E-02  1.28E+00   4.84E-01    5.37E-01   2.29E-02   0.00E+00    5.50E-03  4.56E-03
                        76-Z       77-Y        34-Z       36-Y   0.00E+00              8.47E-02
                   -5.76E-01  -2.70E-01   -2.66E-02  -8.00E-03

 ITE=  3  3.47E-04  2.84E+00   3.04E-01    1.39E-02   6.10E-04   0.00E+00    6.48E-05  1.01E-02
                        76-X       77-Y        34-Z       36-Y   0.00E+00              5.31E-02
                    1.12E+00  -1.19E-01   -7.24E-04  -2.34E-04
```

CODE (C / C++ / Fortran)

```
[Problem_Pinched_Cylinder_Octant]

[FNFEM_shell_MITC4]

-------------------------------------------------------------------
Young's modulus :  3.000E+04, Possion ratio :  0.300E+00
thickness :   1.00E+00
# total elements :      1600,  # total nodes :      1681
# total DOFs :   8405,  # free DOFs :   8079,  # fix DOFs :    326
# of load step :  100
Newton-Rhapson iteration tolerance :   1.00E-03
required memory =  1.258E+01 MB
-------------------------------------------------------------------

1/ Newton-Rhapson iteration

     step    iter    OOB(energy)  norm(OOB(R-F))   norm(disp)    norm(rot)     criteria

      99      0       4.76E+00      9.76E+03       5.43E+00      2.02E-01      1.00E+00
      99      1       1.54E+00      9.81E+03       1.82E-01      9.35E-03      3.24E-01
      99      2       6.58E-03      9.81E+03       2.23E-01      9.39E-03      1.38E-03
      99      3       9.70E-06      9.81E+03       2.04E-03      8.83E-05      2.04E-06

     100      0       5.35E+00      9.81E+03       6.31E+00      2.40E-01      1.00E+00
     100      1       3.23E+00      9.88E+03       2.20E-01      1.23E-02      6.04E-01
     100      2       2.94E-02      9.88E+03       5.37E-01      2.29E-02      5.50E-03
     100      3       3.47E-04      9.88E+03       1.39E-02      6.10E-04      6.48E-05

2/ Printing Output Files
3/ Completed !
```

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~~Membrane locking~~

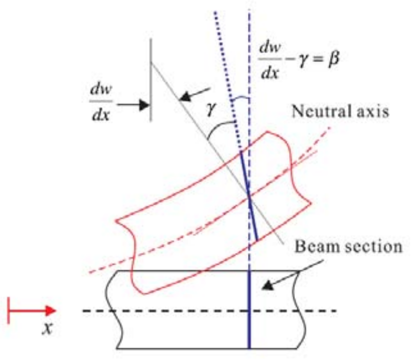
Shell element = membrane element + plate element

Transverse shear locking

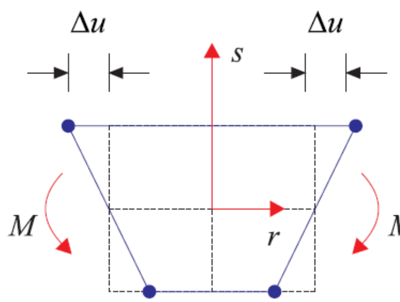
- In-plane shear locking
- Trapezoidal locking
- ~~Volumetric locking~~

Locking problems in 3-node shell elements

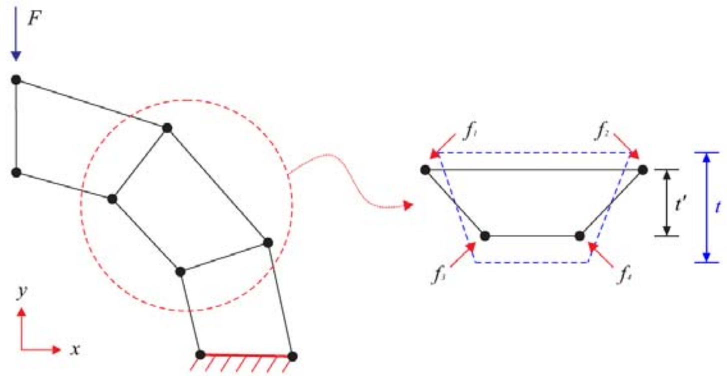
Transverse shear locking



In-plane shear locking



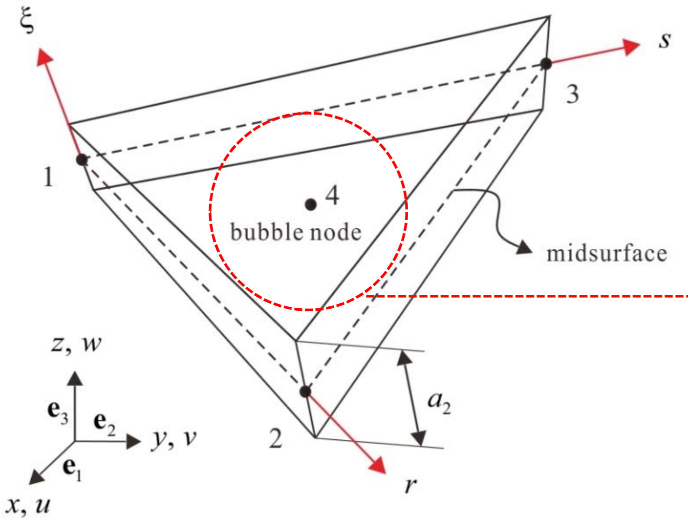
Trapezoidal locking



Two types of newly developed triangular shell elements

PU based MITC3+ (Enriched MITC3+)
- **MITC3+**
  - Transverse shear locking
  - ~~Membrane locking~~
- In-plane shear / Trapezoidal / ~~Volumetric locking~~

	MITC3+	Enriched MITC3+
1. BASIS	Original MITC3 shell element	MITC3+ shell element
2. METHODS	Cubic bubble function	Cubic bubble function Partition of unity approximation
4. FEATURE	Improved bending behaviors	Improved bending / membrane behaviors



Original 3-node shell element

$$\mathbf{u}(r,s,\xi)=\sum_{i=1}^{3}h_i(r,s)\mathbf{u}_i+\frac{\xi}{2}\sum_{i=1}^{3}a_ih_i(r,s)(-\mathbf{V}_2^i\alpha_i+\mathbf{V}_1^i\beta_i)$$

3-node shell element with the bubble function

$$\mathbf{u}(r,s,\xi)=\sum_{i=1}^{3}h_i(r,s)\mathbf{u}_i+\frac{\xi}{2}\sum_{i=1}^{4}a_if_i(r,s)(-\mathbf{V}_2^i\alpha_i+\mathbf{V}_1^i\beta_i)$$

➡ Suggested new assumed strain fields ➡ MITC3+ shell element

- Lee Y et al., The MITC3+ shell element and its performance, Comput Struct 2014;138:12-23
- Excellent convergence behavior
- Only linear analysis conditions have been considered

Kinematics

Incremental Green-Lagrange strain tensor components :

$$ {}_0\varepsilon_{ij} = \frac{1}{2}\left({}^{t+\Delta t}\mathbf{g}_i \cdot {}^{t+\Delta t}\mathbf{g}_j - {}^{t}\mathbf{g}_i \cdot {}^{t}\mathbf{g}_j\right) = \frac{1}{2}\left(\mathbf{u}_{,i} \cdot {}^{t}\mathbf{g}_j + {}^{t}\mathbf{g}_i \cdot \mathbf{u}_{,j} + \mathbf{u}_{,i} \cdot \mathbf{u}_{,j}\right) $$

nonlinear part in the GL strain

Displacement interpolation with finite rotations :

$$ \mathbf{u} = \sum_{i=1}^{3} h_i(r,s)\mathbf{u}_i + \frac{t}{2}\sum_{i=1}^{4} a_i f_i \left[-\alpha_i\, {}^{t}\mathbf{V}_2^i + \beta_i\, {}^{t}\mathbf{V}_1^i - \frac{1}{2}(\alpha_i^2 + \beta_i^2)\, {}^{t}\mathbf{V}_n^i \right] $$

cf. linear analysis $\mathbf{u} = \sum_{i=1}^{3} h_i \mathbf{u}_i + \sum_{i=1}^{4} \frac{t}{2} a_i f_i \left(-\mathbf{V}_2^i \alpha_i + \mathbf{V}_1^i \beta_i \right)$

Iterative solution procedures

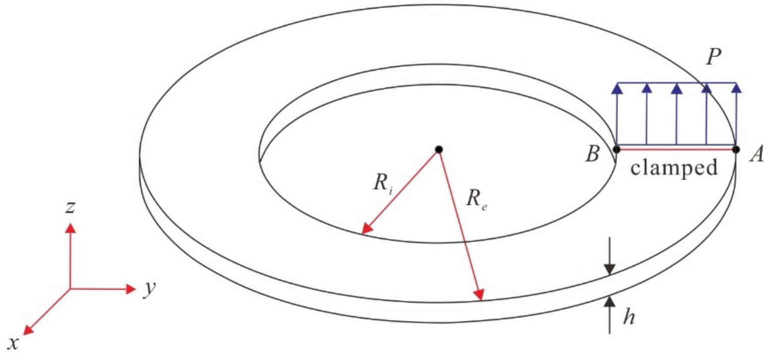
With the full Newtorn-Raphson iteration scheme, the equation for the *i*-th iteration in a finite element model are

$$ {}_0^t\mathbf{K}^{(i-1)} \Delta \mathbf{U}^{(i)} = {}^{t+\Delta t}\Re - {}_0^t\mathbf{F}^{(i-1)} $$

for the displacement,

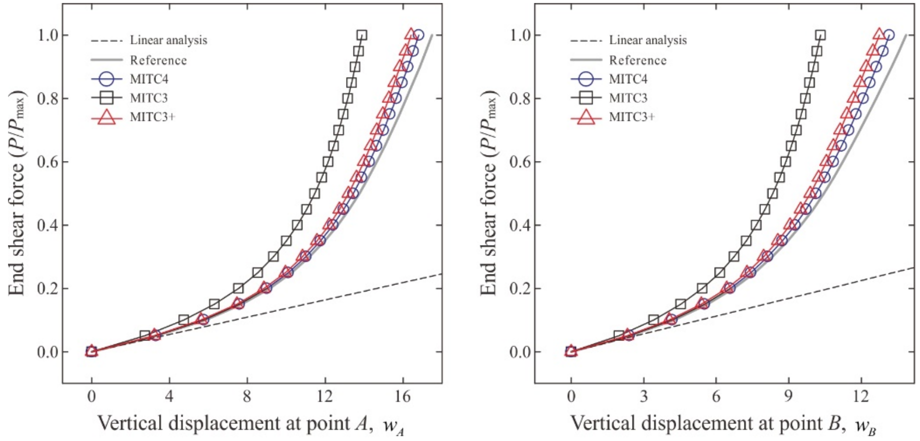
$$ {}^{t+\Delta t}\mathbf{U}^{(i)} = {}^{t+\Delta t}\mathbf{U}^{(i-1)} + \Delta \mathbf{U}^{(i)} $$

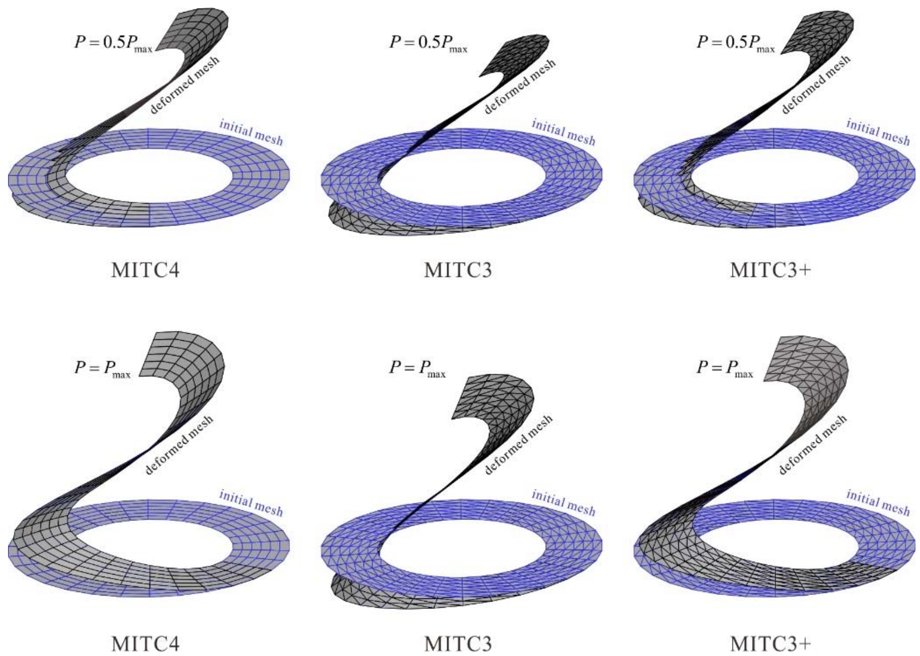
Slit annular plate problem



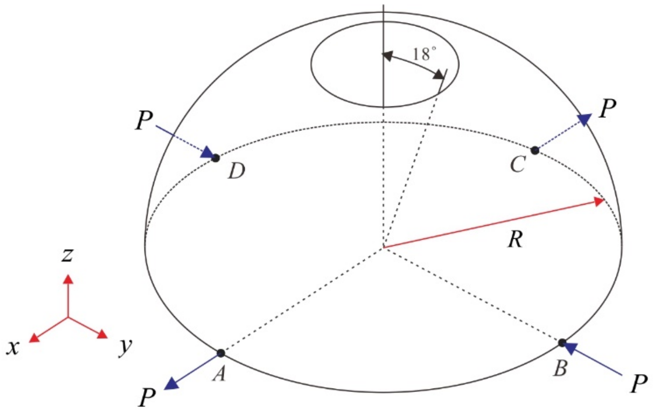
$$R_i = 6,\ R_e = 10,\ h = 0.03,\ P = 3.2$$
$$E = 21\times 10^6,\ \nu = 0$$

Element	Description
MITC4	4-node quadrilateral shell element (Bathe, 1986)
MITC3	3-node triangular shell element (Lee, 2004)
MITC3+	3-node triangular shell element with a cubic bubble function (present)
Reference	9-node quadrilateral shell element





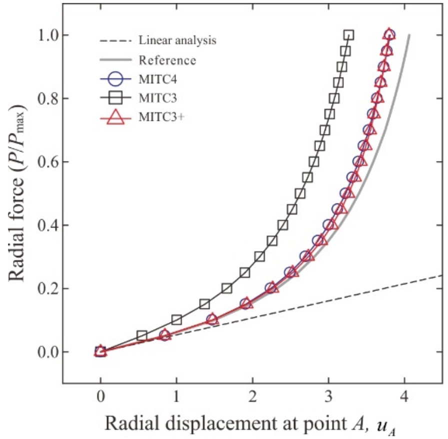
Hemisphere shell problem

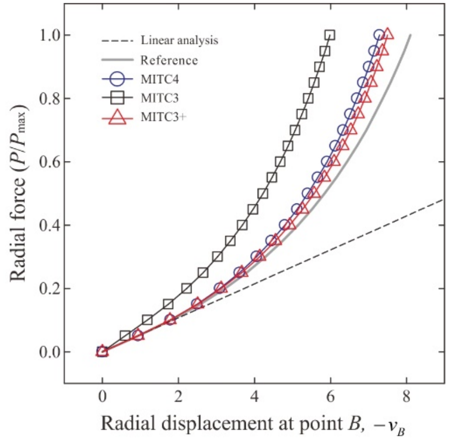


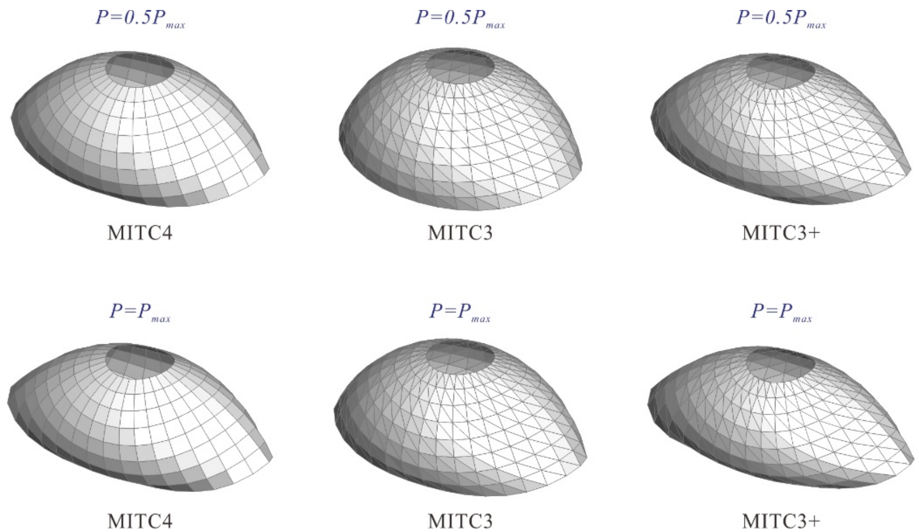
$R = 10,\ h = 0.04,\ P = 400$

$E = 6.825 \times 10^{7},\ \nu = 0.3$

Element	Description
MITC4	4-node quadrilateral shell element (Bathe, 1986)
MITC3	3-node triangular shell element (Lee, 2004)
MITC3+	3-node triangular shell element with a cubic bubble function (present)
Reference	9-node quadrilateral shell element

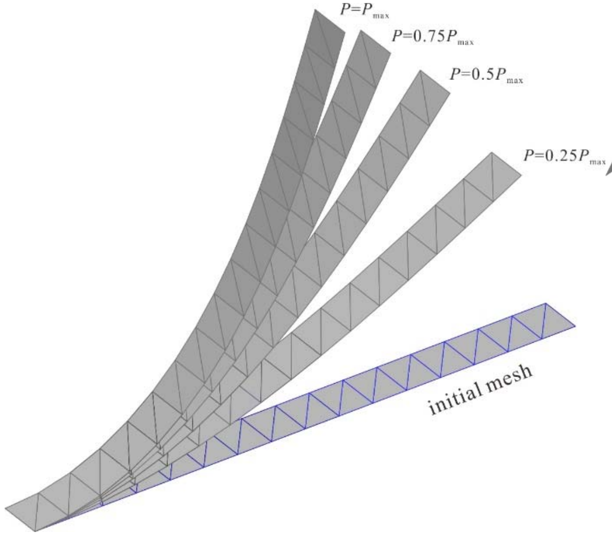


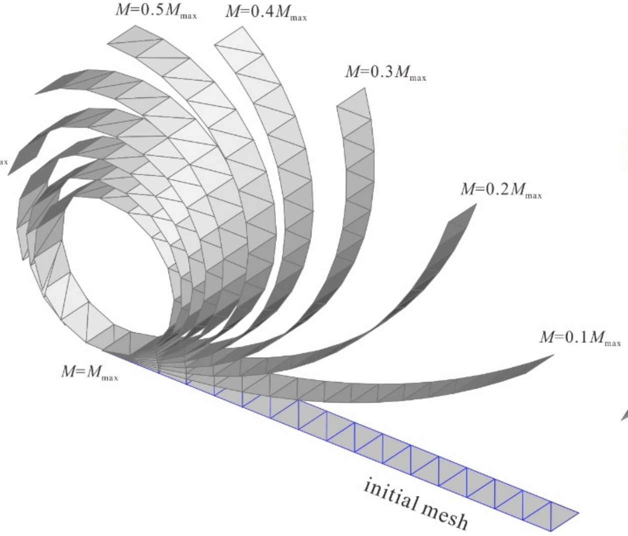




Nonlinear performances of the MITC3+ element #3 – Other problems

Other benchmark problems solved





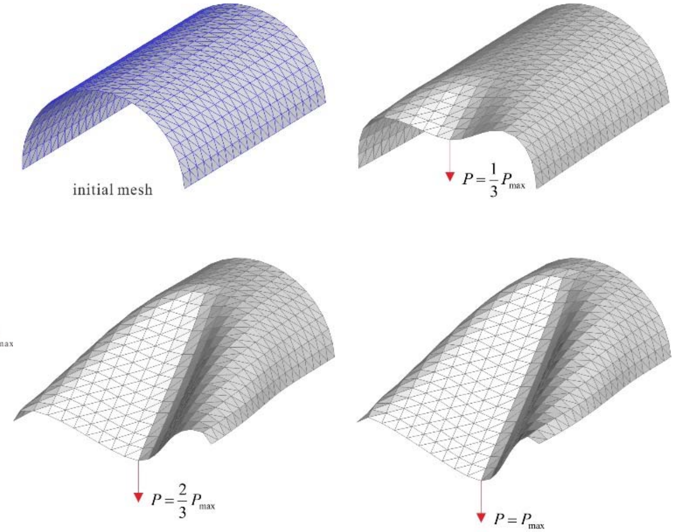
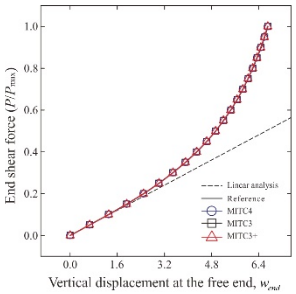
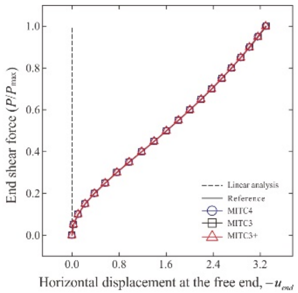


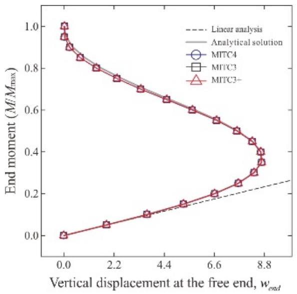
Plate under end shear force

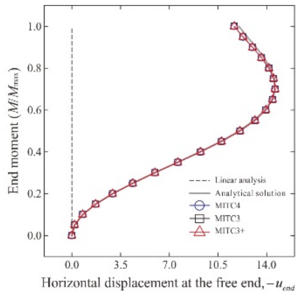
Plate subjected to end moment

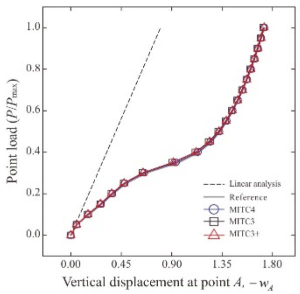
Clamped semi-cylindrical shell

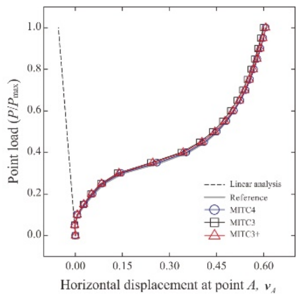












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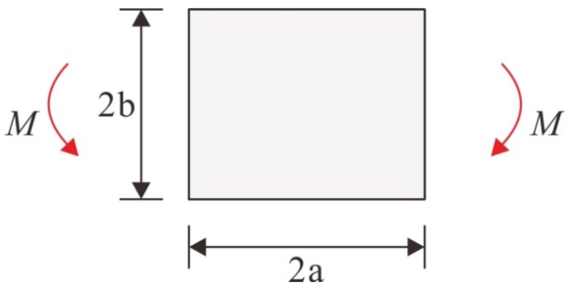
Two types of newly developed triangular shell elements

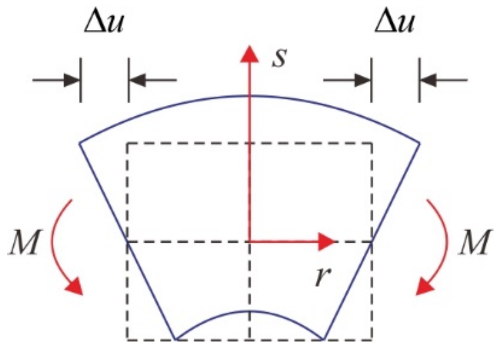
PU based MITC3+ (Enriched MITC3+)
- **MITC3+**
  - Transverse shear locking
  - ~~Membrane locking~~
- In-plane shear / Trapezoidal / ~~Volumetric locking~~

	MITC3+	Enriched MITC3+
1. BASIS	Original MITC3 shell element	MITC3+ shell element
2. METHODS	Cubic bubble function	Cubic bubble function
		Partition of unity approximation
4. FEATURE	Improved bending behaviors	Improved bending / membrane behaviors

Pure bending 2D problem



Correct beam deformation

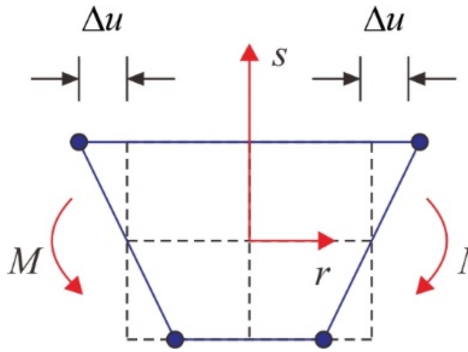


$$u(r,s) = \frac{M}{EI} rs$$

$$v(r,s) = \frac{Ma^2}{2EI}\left(1 - \frac{r^2}{a^2}\right) + \frac{Mb^2}{2EI}\left(1 - \frac{s^2}{b^2}\right)$$

$$\gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} = 0$$

Finite element deformation



$$u(r,s) = \Delta u rs$$

$$v = 0$$

$$\gamma_{xy} = \Delta u r$$

Parasitic in-plane shear strain

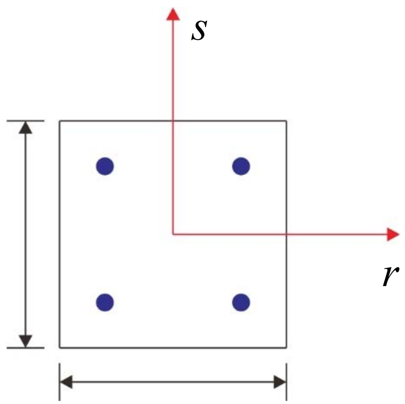
In-plane shear locking : The element has an excess of shear strain which contribute to the poor ability of the element to reproduce bending modes.

The methods to improve membrane behaviors

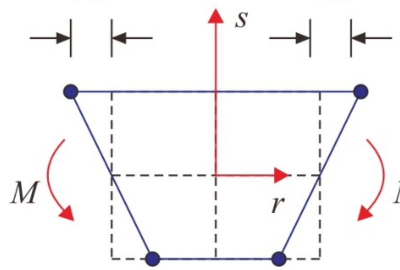
- Reduced Integration method
- Incompatible mode
- Additional bubble node
- Assumed Natural Strain(ANS) method
- Drilling degrees of freedom
- Enhanced Assumed Strain(EAS) method
- Discrete Shear Gap (DSG) method
- ….
- Partition of unity approximations

Comparison with other methods #2 – Reduced Integration method

Gauss quadrature $I = \int_{-1}^{1}\int_{-1}^{1} f(r,s)\, ds dt \simeq \sum_{i=1}^{M}\sum_{j=1}^{M} W_{ij} f(r_i, s_j)$



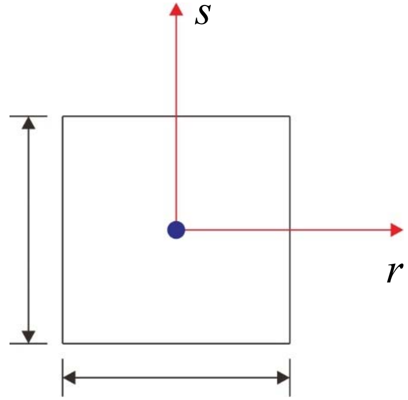
Full integration



$u(r,s) = \Delta urs$

$v = 0$

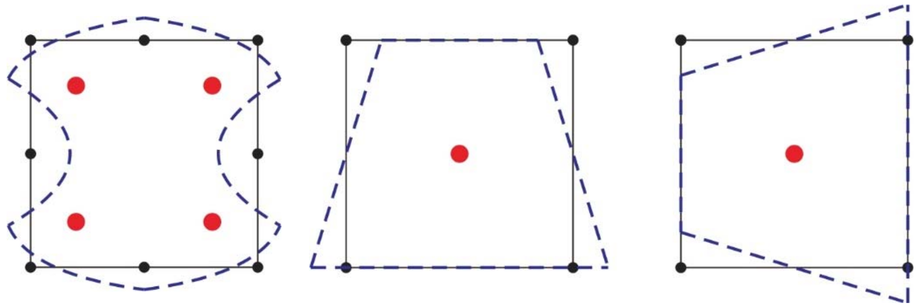
$\gamma_{xy} = \Delta ur$



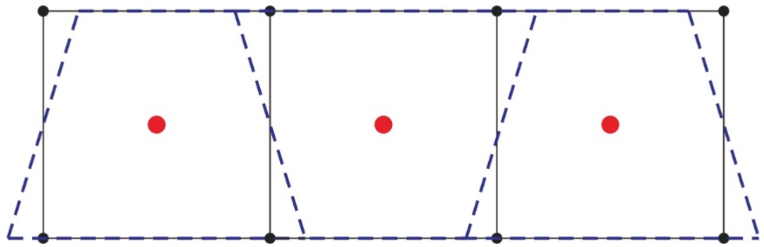
Reduced integration
(Zienkiewicz OC et al., 1971)

Geometric-invariant
Quadrilateral element

Hourglass control (Flanagan & Belytschko, 1981)

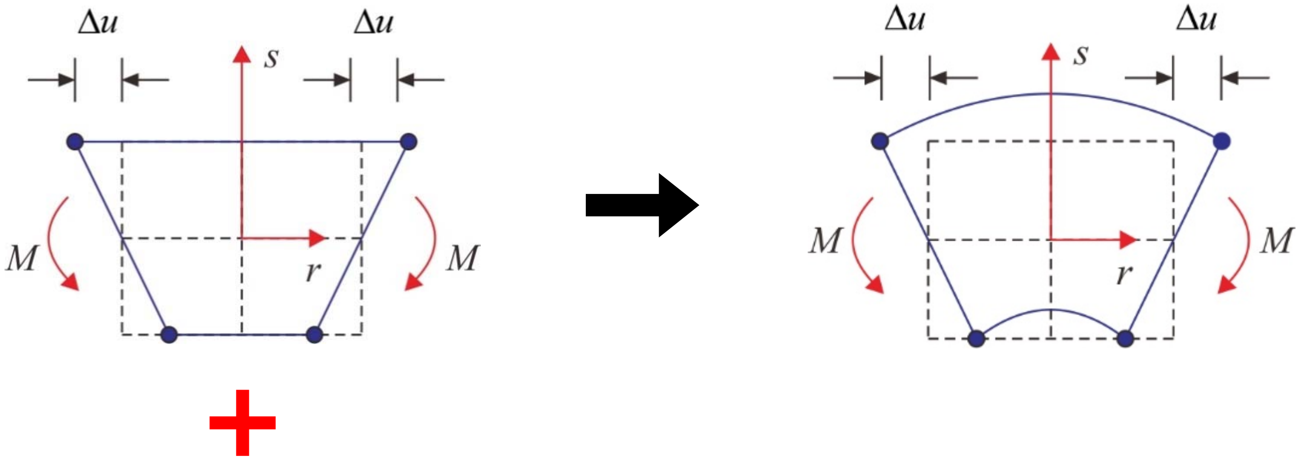


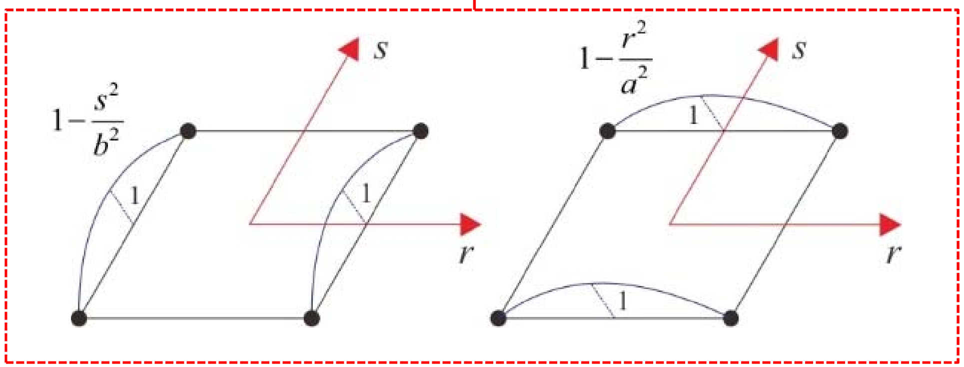
2 hour–glass modes



Propagation of hour-glass modes through a mesh

Incompatible modes





Incompatible modes (Wilson(1971), Taylor(1976))

$$u = \sum_{i=1}^{4} N_i u_i + \left(1-\frac{r^2}{a^2}\right)u_5 + \left(1-\frac{s^2}{b^2}\right)u_6$$

$$v = \sum_{i=1}^{4} N_i v_i + \left(1-\frac{r^2}{a^2}\right)v_5 + \left(1-\frac{s^2}{b^2}\right)v_6$$

- Only 4-node quadrilateral element
- Spurious energy in nonlinear analysis

(Sussman T and Bathe KJ, Comput Struct, 2014)

Partition of unity approximation

$$\bar{u}(\mathbf{x}) = \sum_{i=1}^{3} h_i u_i + \sum_{i=1}^{3} h_i (x - x_i) a_{2i} + h_i (y - y_i) a_{3i}$$

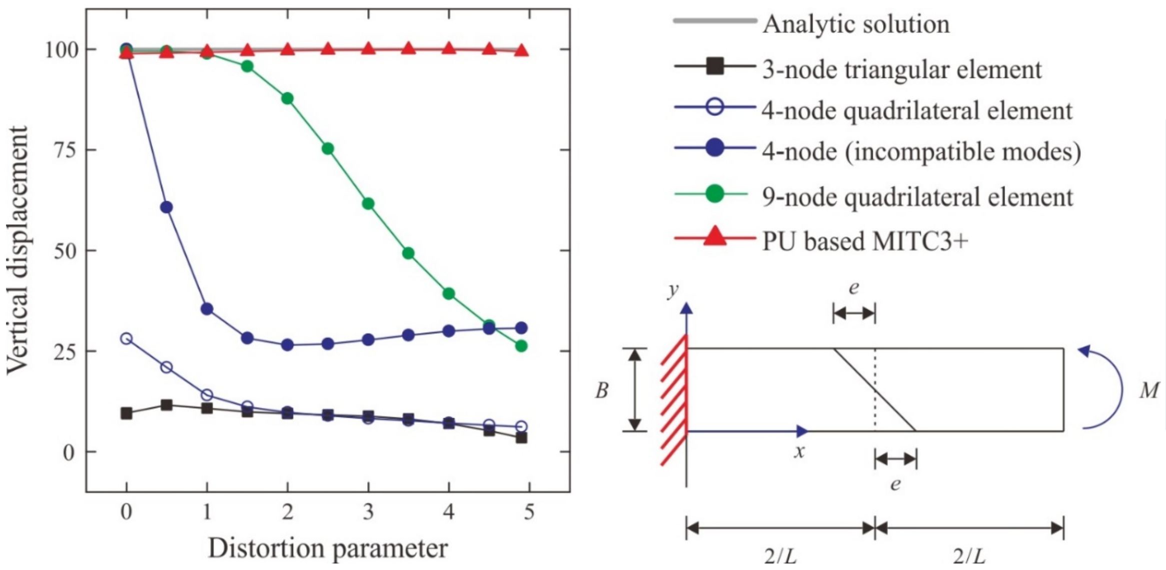
Standard term — Additional term

$$\bar{u}(\mathbf{x}) = u(x) + \hat{u}(x)$$

$$u(x) = \sum_{i=1}^{3} h_i u_i$$

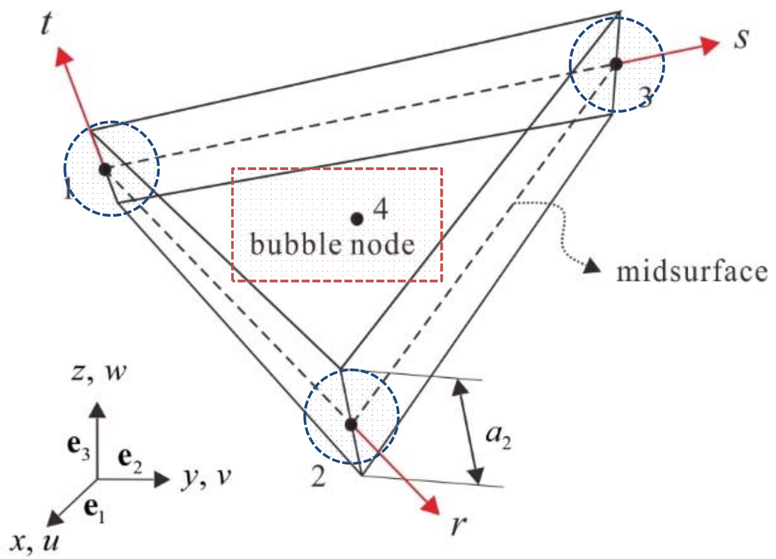
$$\hat{u}(x) = \sum_{i=1}^{3} h_i (x - x_i) a_{2i} + h_i (y - y_i) a_{3i}$$

Distortion sensitivity test



Advantages

- 3-node triangular element
- Geometric invariant
- Pass basic tests
- Accurate results than other methods



$$\begin{bmatrix} e_{xx} \\ e_{yy} \\ e_{xy} \\ e_{yz} \\ e_{zx} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} \frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{u}}{\partial x} \\ \frac{\partial \bar{v}}{\partial y} + \frac{\partial \bar{v}}{\partial y} \\ \frac{\partial \bar{u}}{\partial y} + \frac{\partial \bar{v}}{\partial x} \\ \frac{\partial \bar{v}}{\partial z} + \frac{\partial \bar{w}}{\partial y} \\ \frac{\partial \bar{w}}{\partial x} + \frac{\partial \bar{u}}{\partial z} \end{bmatrix}$$

High order interpolation (enhanced membrane)

MITC method (transverse shear locking)

Original 3-node displacement interpolation

$$\mathbf{u} = \sum_{i=1}^{3} h_i \mathbf{u}_i + \frac{t}{2} \sum_{i=1}^{3} a_i h_i (-\mathbf{V}_2^i \alpha_i + \mathbf{V}_1^i \beta_i), \text{ with } \mathbf{u} = [u \ \ v \ \ w]^T$$

PU based MITC3+ (Enriched MITC3+)

$$\begin{cases} \bar{u} = \sum_{i=1}^{3} h_i u_i + \frac{t}{2} \sum_{i=1}^{4} a_i f_i (-\mathbf{V}_2^i \alpha_i + \mathbf{V}_1^i \beta_i) + \hat{u} \\ \bar{v} = \sum_{i=1}^{3} h_i v_i + \frac{t}{2} \sum_{i=1}^{4} a_i f_i (-\mathbf{V}_2^i \alpha_i + \mathbf{V}_1^i \beta_i) + \hat{v} \\ \bar{w} = \sum_{i=1}^{3} h_i w_i + \frac{t}{2} \sum_{i=1}^{4} a_i f_i (-\mathbf{V}_2^i \alpha_i + \mathbf{V}_1^i \beta_i) \end{cases}$$

MITC3+ shell element

PU approximation

PU based MITC3+ shell element (Enriched MITC3+)

Kinematics

Incremental Green-Lagrange strain tensor components :

$${}_0\varepsilon_{ij} = \frac{1}{2}({}^{t+\Delta t}\mathbf{g}_i \cdot {}^{t+\Delta t}\mathbf{g}_j - {}^{t}\mathbf{g}_i \cdot {}^{t}\mathbf{g}_j) = \frac{1}{2}(\bar{\mathbf{u}}_{,i} \cdot {}^{t}\bar{\mathbf{g}}_j + {}^{t}\bar{\mathbf{g}}_i \cdot \bar{\mathbf{u}}_{,j} \boxed{+ \bar{\mathbf{u}}_{,i} \cdot \bar{\mathbf{u}}_{,j}})$$

nonlinear part in the GL strain

Finite rotations :

Linear $$\bar{\mathbf{u}} = \sum_{i=1}^{3} h_i \mathbf{u}_i + \sum_{i=1}^{4} \frac{t}{2} a_i f_i \left(-\mathbf{V}_2^i \alpha_i + \mathbf{V}_1^i \beta_i\right) + \hat{\mathbf{u}}$$

Nonlinear $$\bar{\mathbf{u}} = \sum_{i=1}^{3} h_i(r,s)\mathbf{u}_i + \frac{t}{2}\sum_{i=1}^{4} a_i f_i \left[-\alpha_i\, {}^{t}\mathbf{V}_2^i + \beta_i\, {}^{t}\mathbf{V}_1^i \boxed{- \frac{1}{2}(\alpha_i^2 + \beta_i^2)\, {}^{t}\mathbf{V}_n^i}\right] + \hat{\mathbf{u}}$$

Iterative solution procedures

With the full Newtorn-Raphson iteration scheme, the equation for the *i*-th iteration in a finite element model are

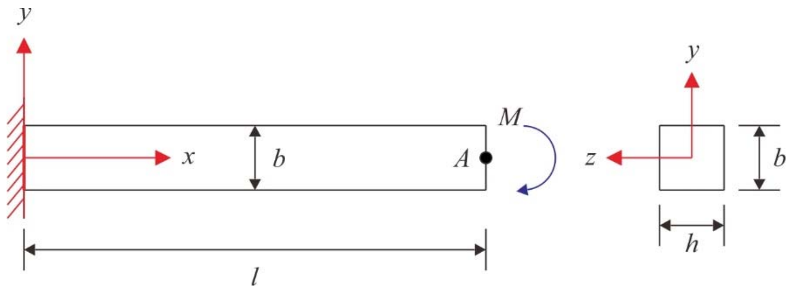
$${}_0^t\mathbf{K}^{(i-1)} \Delta \mathbf{U}^{(i)} = {}^{t+\Delta t}\Re - {}_0^t\mathbf{F}^{(i-1)}$$

for the displacement,

$${}^{t+\Delta t}\mathbf{U}^{(i)} = {}^{t+\Delta t}\mathbf{U}^{(i-1)} + \Delta \mathbf{U}^{(i)}$$

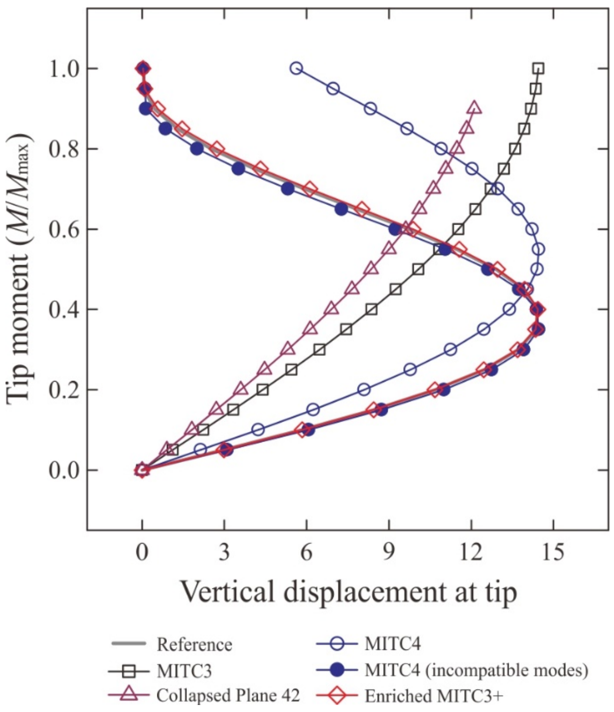
Performances of the PU based MITC3+ element #1

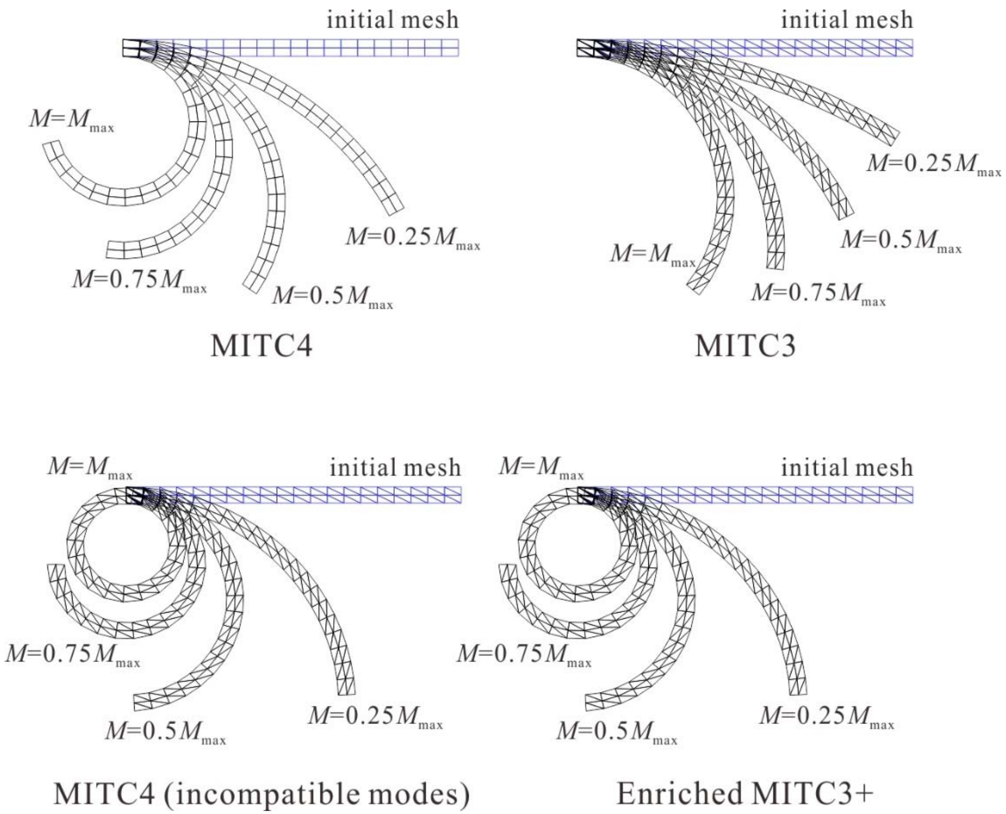
Cantilever beam subjected a tip moment



$l = 20,\ b = h = 1,\ M = 10\pi$

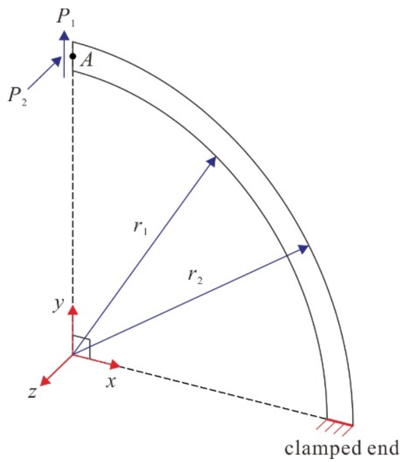
$E = 1200,\ \nu = 0.2$





Performances of the PU based MITC3+ element #2

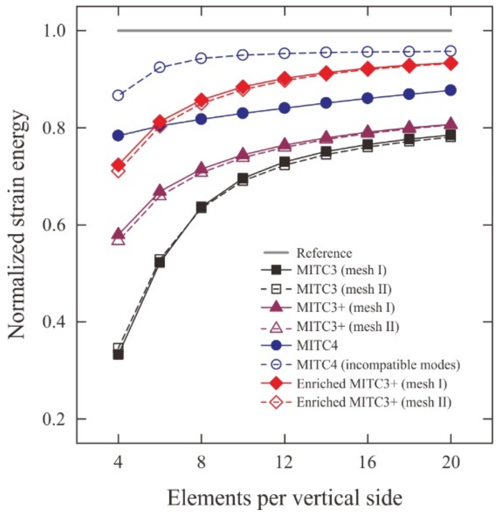
Curved cantilever beam

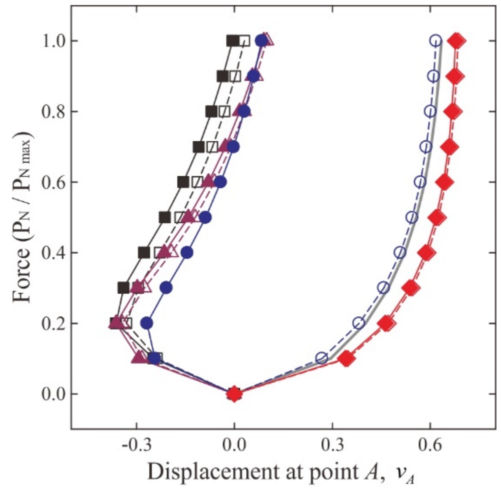


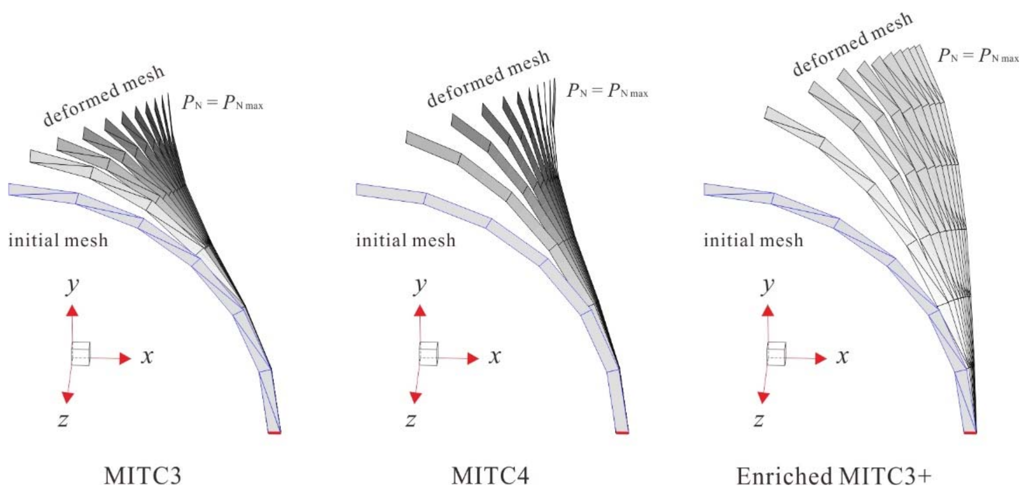
$$R_1 = 4.12,\ R_2 = 4.32,\ h = 0.1$$

$$E = 1\times10^7,\ \nu = 0.25$$

Element	Description
MITC4	4-node quadrilateral shell element (Bathe, 1986)
MITC3	3-node triangular shell element (Lee, 2004)
MITC3+	3-node triangular shell element with a cubic bubble function (Jeon, 2014)
Enriched MITC3+	PU based MITC3+ (present)
Reference	9-node quadrilateral shell element

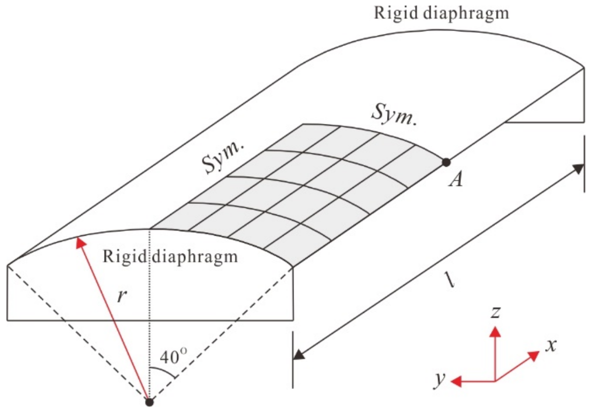






Performances of the PU based MITC3+ element #3

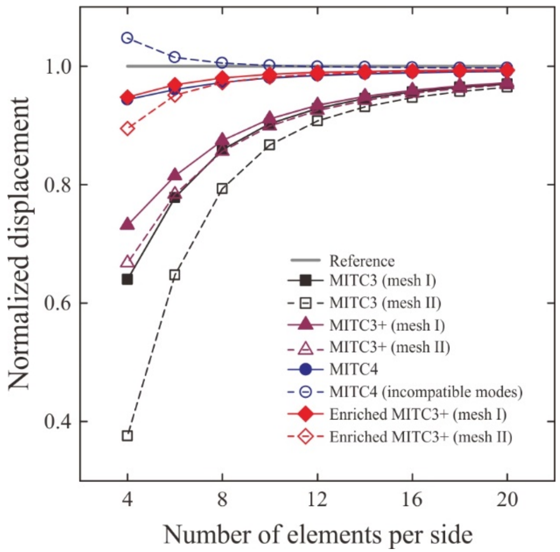
Hemisphere shell problem

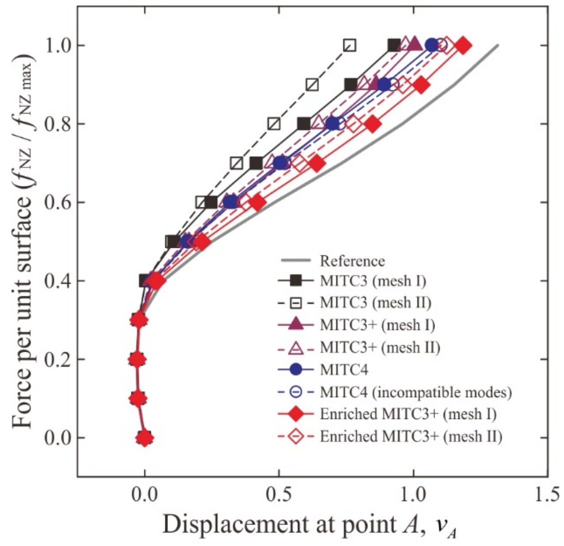


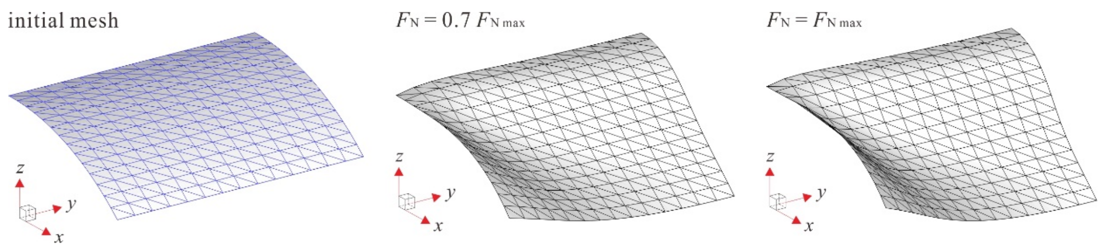
$L = 50,\ R = 25,\ t = 0.25,\ f_z = 90$

$E = 4.32\times10^{8},\ \nu = 0$

Element	Description
MITC4	4-node quadrilateral shell element (Bathe, 1986)
MITC3	3-node triangular shell element (Lee, 2004)
MITC3+	3-node triangular shell element with a cubic bubble function (Jeon, 2014)
Enriched MITC3+	PU based MITC3+ (present)
Reference	9-node quadrilateral shell element







Nonlinear analysis of the MITC3+ shell element published in *Computers and Structures*, Jan 2015

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The MITC3+ shell element in geometric nonlinear analysis

Hyeong-Min Jeon [a], Youngyu Lee [a], Phill-Seung Lee [a,*], Klaus-Jürgen Bathe [b]

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ABSTRACT

In this paper, we present the MITC3+ shell finite element for geometric nonlinear analysis and demonstrate its performance. The MITC3+ shell element, recently proposed for linear analysis [1], represents a further development of the MITC3 shell element. The total Lagrangian formulation is employed allowing for large displacements and large rotations. Considering several analysis problems, the nonlinear solutions using the MITC3+ shell element are compared with those obtained using the MITC3 and MITC4 shell elements. We conclude that the MITC3+ shell element shows, in the problems considered, the same excellent performance in geometric nonlinear analysis as already observed in linear analysis.

The **Enriched MITC3+** shell element will be submitted in *CMAME*

The enriched MITC3+ shell element with improved membrane responses

Hyeong-Min Jeon [a], Kyungho Yoon [a], Phill-Seung Lee [a,*]

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Abstract

In this paper, we develop a partition of unity based triangular shell finite element with improved membrane behaviors. The proposed shell element is based on the MITC3+ shell element which uses a cubic bubble function for the rotations and assumed shear strain fields to alleviate the transverse shear locking. In order to membrane behavior, the partition of unity approximation are applied only membrane part of the MITC3+ shell element. For geometric nonlinear analysis, the total Lagrangian formulation is employed allowing for large displacements and rotations. The present shell element passes the basic tests (the isotropy, patch and zero mode tests) and shows excellent convergence behavior in several benchmark problems.

Future works #1 – PU based finite element method with the FE error estimation

PROGRAMMING — UCIrvine | University of California

IFEM

iFEM is a MATLAB software package containing robust, efficient, and easy-following codes for the main building blocks of adaptive finite element methods on unstructured simplicial grids in both two and three dimensions. Besides the simplicity and readability, sparse matrixlization, an innovative programming style for MATLAB, is introduced to improve the efficiency. In this novel coding style, the sparse matrix and its operations are used extensively in the data structure and algorithms.

- A brief Introduction.
- My lecture notes Programming of Finite Element Methods in Matlab
- Dowload the latest version from ifem repository on bitbucket.
- If you have installed Mercurial, you can

```
hg clone https://bitbucket.org/ifem/ifem
```

Integrating the PU based FEM with the error estimator

- Mesh generation
- Adaptive mesh refinement algorithm
- Error estimates
- Coupling method or indicator

KAIST CMSS Computational Mechanics Structural Systems

Future works #2 – PU based finite element method with reduced integration

4-node partition of unity based finite shell element : ~~*Linear dependency problem*~~

<u>2D solid element :</u>

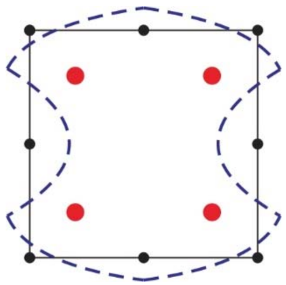
No locking treatments due to the high order interpolation

<u>Shell element :</u>

Absolutely needs to reduce the <u>transverse shear locking</u> even using the high order interpolation

- MITC4-MITC9-MITC16 – Too much computational cost
- MITC4-Reduced Integration – Effectively decrease in computational time
- Reduced Integration – Reduced Integration – Much faster than others

Hourglass mode



8-node serendipity element

$$\bar{e} = e + \hat{e}$$

MITC4
Reduced Integration

MITC9 / MITC16
Reduced Integration

"Parallel programming ***is not a trivial task*** *in most programming languages, and demands a great* ***theoretical knowledge*** *about the hardware architecture and good programming skills" - Neto DP-*

Linux Cluster | Windows Cluster | GPU Cluster | WCU Cluster

Tesla Cluster

- 4-Tesla T10 Graphics Processing Units (GPUs)
- 960-cores (240 processor cores for each GPU)
- 16GB high speed memory (4GB for each GPU)
- Host CPU: Intel Xeon x64 QC Dual Processor
- Host RAM: 2G * 12ea = 24GB

Tesla Workstation (2 sets)

- 4-Tesla C1060 Graphics Processing Units (GPU
- 960-cores (240 processor cores for each GPU)
- 16GB high speed memory (4GB for each GPU)
- Host CPU: Intel Xeon x64 QC Dual Processor
- Host RAM: 4G * 8ea = 32GB

Partition of unity based shell finite element

$$\bar{u}(\mathbf{x}) = u + \hat{u}$$

$$u = \sum_{i=1}^{3} h_i u_i$$

$$\hat{u} = \sum_{i=1}^{3} h_i (x - x_i) a_{2i} + h_i (y - y_i) a_{3i}$$

"The computing of each local matrix is totally independent and so parallelization of these computations is straightforward and can be naturally explored"

Conclusions

- We proposed two possibilities of using the partition of unity approximation
  - ✓ Increase solution accuracy without local mesh refinements (Part I)
  - ✓ Improvement membrane behaviors (part II)

I. PU based MITC3 shell finite element (Enriched MITC3) is reviewed.

- This element is obtained by applying linear displacement interpolation covers to the standard 3-node shell element and MITC procedures are used.
- The method increases the solution accuracy **without any local mesh refinement**.
- We can provide convenience for user by combining PU shell element and FE error estimates.

II. PU based MITC3+ shell finite element (Enriched MITC3+) is proposed.

- This shell element is based on the MITC3+ shell element and partition of unity approximations **to improve membrane response**.
- Membrane behaviors of the triangular shell element efficiently is improved by partition of unity approximation.

Conclusion remarks – Most downloaded papers

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December 2011
Sinan Korkmaz

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3. The MITC3 shell finite element enriched by interpolation covers

1 April 2014
Hyeong-Min Jeon | Phill-Seung Lee | Klaus-Jürgen Bathe

In this paper, we develop a scheme to enrich the 3-node triangular MITC shell finite element by interpolation cover functions. The MITC method is used for the standard and enriched displacement interpolations....

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CST2014

The Twelfth International Conference on Computational Structures Technology

Naples, Italy
2-5 September 2014

Introduction

This is the Twelfth Conference in the Computational Structures Technology series that commenced in 1991. Previous venues for the conference have included: Budapest, Edinburgh, Prague, Leuven, Lisbon, Gran Canaria, Athens, Valencia and Dubrovnik. The conference is concerned with the application of the latest computational technology to structural mechanics and engineering. Computational Technology encompasses both the latest hardware and software developments as well as algorithmic and theoretical techniques.

Opening Lecture

The CST2014 Conference will be opened jointly with the ECT2014 Conference with a lecture presented by Professor K.J. Bathe of Massachusetts Institute of Technology, Cambridge MA, USA.

Frontiers in Finite Element Procedures & Applications (1)

by

Klaus-Jürgen Bathe
Massachusetts Institute of Technology
Cambridge, MA 02139, USA

2 Frontiers in the analysis of shells

The analysis of shells has been pursued for decades and yet there are still important improvements needed in the effectiveness of shell elements. In practice, low-order elements are much preferred because of their ease of use in meshing, their robustness and computational efficiency, but a significant drawback is the rather low accuracy in the calculated stresses. The stress predictions can be improved by the 'stress improvement scheme' published by Payen and Bathe [5] and by the 'interpolation cover scheme' presented by Kim and Bathe [6, 7]. Both schemes were originally developed for the analysis of solids. In the following, we present the development of the interpolation cover scheme for a 3-node shell element, to obtain an enriched formulation [8], and we present a new more powerful 3-node shell element, the MITC3+ element [9]. Since this element formulation is based on the MITC technique, the extension to nonlinear analyses is directly achieved [10].

2.1 The use of interpolation covers for the MITC3 shell element

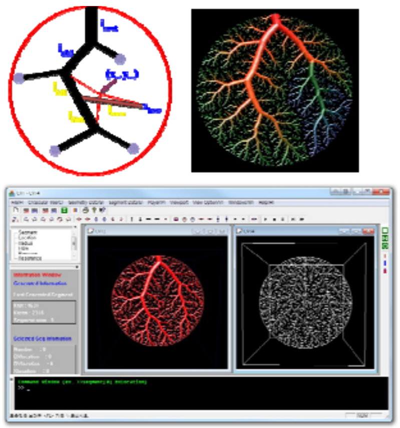
The geometry of the 3-node continuum mechanics based triangular shell finite element is interpolated using [4,11]

$$\mathbf{x}(r,s,t)=\sum_{i=1}^{3} h_i(r,s)\mathbf{x}_i+\sum_{i=1}^{3}\frac{t}{2}a_i h_i(r,s)\mathbf{V}_n^i \quad \text{with } h_1=r,\ h_2=s,\ h_3=1-r-s \qquad (1)$$

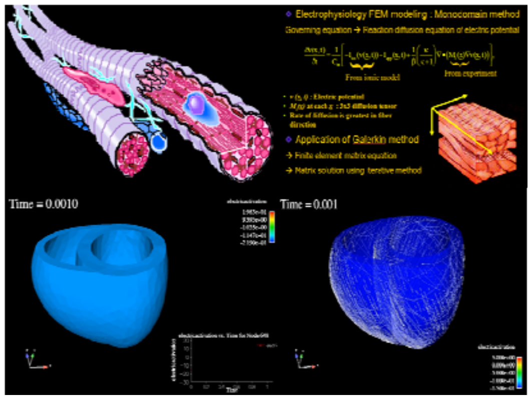
Previous research (2003 ~ 2012)

Kangwon National University

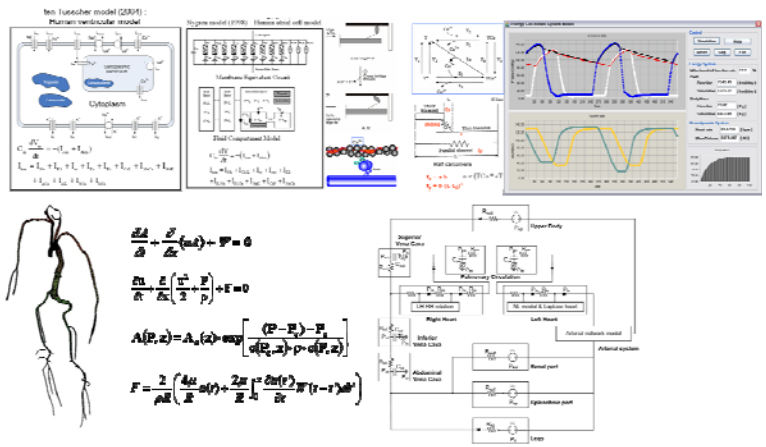
Coronary artery generation



Virtual heart (NRL project)

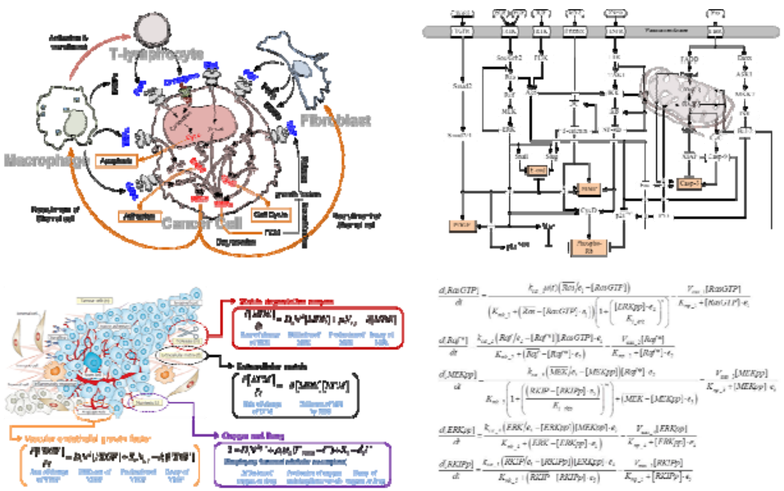


Arterial network with the hemodynamic model

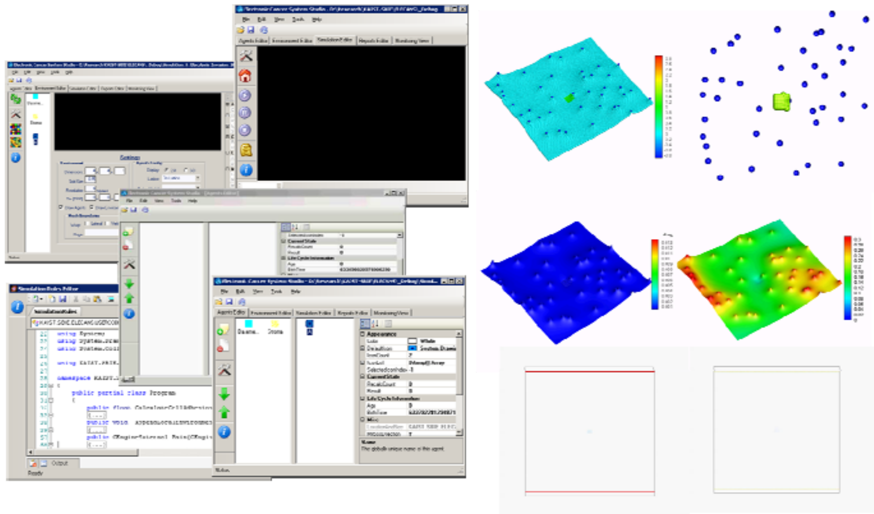


KAIST, SBIE

Virtual cancer system (NRL project)



Angiogenesis and vascular tumor growth



Education & Publications

Education

- Ph.D. Student : Korea advanced Institute of Science and Technology (Sep 2010 - present)
- MS : Kangwon National University (Sep 2006 – Aug 2008)
  (Thesis : Development of a cell-system coupled model of cardiovascular hemodynamics)
- BS : Kangwon National University (Mar 2000 – Aug 2006) (Summa Cum Laude & Early Graduation)

Experience

- URP program, Kangon National University (Sep. 2003 ~ Aug 2006), Dep. of Mechanical Engineering
- Visiting Researcher, Kyoto University (Dec 2007- Mar 2008 and Apr 2009- Jun 2009), Graduate School of Medicine
- Visiting Researcher, MIT (Aug 2008 – Oct 2008), Dep. of Health Sciences and Technology
- Visiting Researcher, Oxford (Jul 2010- Aug 2010), Centre for Mathematical Biology
- Research Assistant, KAIST (Jan 2010 – Aug 2012), Dep. of Bio and Brain Engineering, Advisor : Prof. Kwang-Hyun Cho.

International Journals (published : 4)

1. Jeon HM, Yoon K, Lee PS. A partition of unity based triangular shell element with improved membrane response, In preparation
2. Lee Y, Jeon HM, Lee PS, Bathe KJ. On the behavior of the 3-node MITC triangular shell elements, In preparation.
3. Jeon HM, Lee Y, Lee PS, Bathe KJ. The MITC3+ shell element in geometric nonlinear analysis, Computers and Structures, 146, 91-104, Jan 2015.
4. Jeon HM, Lee PS, Bathe KJ. The MITC3 shell finite element enriched by interpolation covers, Computers and Structures, 134, 128-142, Apr 2014.
5. Shim EB, Jun HM, Leem CH, Matusuoka S, Noma A. A new integrated method using a cell-hemodynamics-autonomic nerve control coupled model of the cardiovascular system. Progress in Biophysics and Molecular Biology, 96(1-3), 44-59, Jan 2008.
6. Jun HM, Shim EB. Theoretical analysis of the cross-bridge sliding rate in modulating heart mechanics, International Journal of Vascular Biomedical Engineering, 5(2), 34-45, Oct 2007.

Presentation (27)

- Jeon HM, Yoon K, Lee PS. Development of the enriched MITC3 shell element. KSME Annual Conference, 192-193, Apr 2014.
- …..
- Computational study on the arterial tree generation based on blood volume optimization. KSME Annual Conference, Oct 2005.