Validation of General Purpose CAE, CFD Simulation Code -hFlow-

hFlow CAE Solution Group

gFlow™ hFlow™ sFlow™ aFlow™

I. Mesh Generation
– gFlow –

gFlow™(Mesh Generation Code)

1. Elliptic mesh generation equation

$$\alpha_{11}x_{\xi\xi}+\alpha_{12}x_{\xi\eta}+\alpha_{13}x_{\xi\phi}+\alpha_{22}x_{\eta\eta}+\alpha_{23}x_{\eta\phi}+\alpha_{33}x_{\phi\phi}=-I^2\left(Px_\xi+Qx_\eta+Rx_\phi\right)$$

2. Control function(P, Q and R) suggested by Thomas and Middlecoff(1980)

3. Jacobian and coefficient

$$I=x_\xi\left(y_\eta z_\phi-y_\phi z_\eta\right)-x_\eta\left(y_\xi z_\phi-y_\phi z_\xi\right)+x_\phi\left(y_\xi z_\eta-y_\eta z_\xi\right)$$

$$\alpha_{11}=\beta_{11}^2+\beta_{21}^2+\beta_{31}^2$$

$$\alpha_{12}=\beta_{11}\beta_{12}+\beta_{21}\beta_{22}+\beta_{31}\beta_{32}$$

$$\alpha_{13}=\beta_{11}\beta_{13}+\beta_{21}\beta_{23}+\beta_{31}\beta_{33}$$

$$\alpha_{22}=\beta_{12}^2+\beta_{22}^2+\beta_{32}^2$$

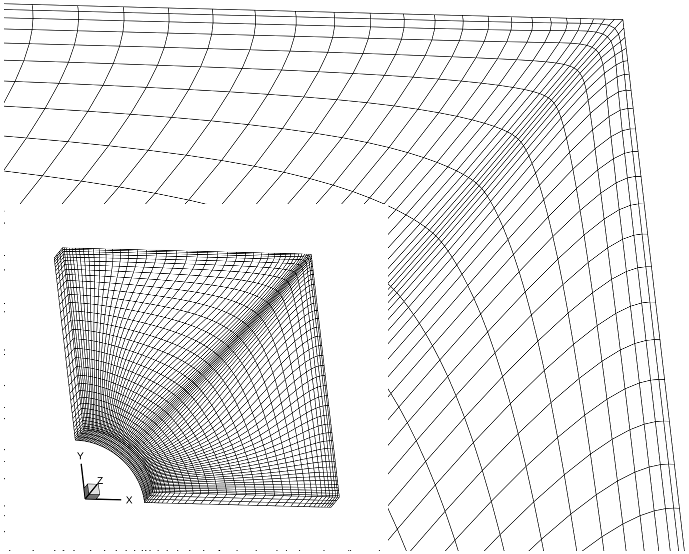
$$\alpha_{23}=\beta_{12}\beta_{13}+\beta_{22}\beta_{23}+\beta_{32}\beta_{33}$$

$$\alpha_{33}=\beta_{13}^2+\beta_{23}^2+\beta_{33}^2$$

$$\beta_{11}=y_\eta z_\phi-y_\phi z_\eta\,,\ \beta_{12}=y_\phi z_\xi-y_\xi z_\phi\,,\ \beta_{13}=y_\xi z_\eta-y_\eta z_\xi$$

$$\beta_{21}=x_\phi z_\eta-x_\eta z_\phi\,,\ \beta_{22}=x_\xi z_\phi-x_\phi z_\xi\,,\ \beta_{23}=x_\eta z_\xi-x_\xi z_\eta$$

$$\beta_{31}=x_\eta y_\phi-x_\phi y_\eta\,,\ \beta_{32}=x_\phi y_\xi-x_\xi y_\phi\,,\ \beta_{33}=x_\xi y_\eta-x_\eta y_\xi$$



4. Mesh generation using gFlow™

- High orthogonality
- Desired space control
- High smoothness

II. Convection and Diffusion Scheme – hFlow –

hFlow CAE Solution Group

gFlow™ hFlow™ sFlow™ aFlow™

hFlow™(Heat, Mass & Fluid Flow Analysis Code)

1. u-Momentum Equation

$$\frac{\partial}{\partial\xi}(\rho Uu)+\frac{\partial}{\partial\eta}(\rho Vu)+\frac{\partial}{\partial\phi}(\rho Wu)=-\left(f_{11}\frac{\partial p}{\partial\xi}+f_{21}\frac{\partial p}{\partial\eta}+f_{31}\frac{\partial p}{\partial\phi}\right)$$
$$+\frac{\partial}{\partial\xi}\left[\frac{\Gamma}{J}\left(q_{11}\frac{\partial u}{\partial\xi}+q_{12}\frac{\partial u}{\partial\eta}+q_{13}\frac{\partial u}{\partial\phi}\right)\right]$$
$$+\frac{\partial}{\partial\eta}\left[\frac{\Gamma}{J}\left(q_{21}\frac{\partial u}{\partial\xi}+q_{22}\frac{\partial u}{\partial\eta}+q_{23}\frac{\partial u}{\partial\phi}\right)\right]$$
$$+\frac{\partial}{\partial\phi}\left[\frac{\Gamma}{J}\left(q_{31}\frac{\partial u}{\partial\xi}+q_{32}\frac{\partial u}{\partial\eta}+q_{33}\frac{\partial u}{\partial\phi}\right)\right]$$

2. Energy Equation

$$\frac{\partial}{\partial\xi}(\rho UH)+\frac{\partial}{\partial\eta}(\rho VH)+\frac{\partial}{\partial\phi}(\rho WH)$$
$$=\frac{\partial}{\partial\xi}\left[\frac{\Gamma_h}{J}\left(q_{11}\frac{\partial h}{\partial\xi}+q_{12}\frac{\partial h}{\partial\eta}+q_{13}\frac{\partial h}{\partial\phi}\right)\right]+\frac{\partial}{\partial\eta}\left[\frac{\Gamma_h}{J}\left(q_{21}\frac{\partial h}{\partial\xi}+q_{22}\frac{\partial h}{\partial\eta}+q_{23}\frac{\partial h}{\partial\phi}\right)\right]$$
$$+\frac{\partial}{\partial\phi}\left[\frac{\Gamma_h}{J}\left(q_{31}\frac{\partial h}{\partial\xi}+q_{32}\frac{\partial h}{\partial\eta}+q_{33}\frac{\partial h}{\partial\phi}\right)\right]+\frac{\partial}{\partial\xi}\left[\frac{\Gamma_k}{J}\left(q_{11}\frac{\partial k}{\partial\xi}+q_{12}\frac{\partial k}{\partial\eta}+q_{13}\frac{\partial k}{\partial\phi}\right)\right]$$
$$+\frac{\partial}{\partial\eta}\left[\frac{\Gamma_k}{J}\left(q_{21}\frac{\partial k}{\partial\xi}+q_{22}\frac{\partial k}{\partial\eta}+q_{23}\frac{\partial k}{\partial\phi}\right)\right]+\frac{\partial}{\partial\phi}\left[\frac{\Gamma_k}{J}\left(q_{31}\frac{\partial k}{\partial\xi}+q_{32}\frac{\partial k}{\partial\eta}+q_{33}\frac{\partial k}{\partial\phi}\right)\right]$$
$$+\Phi$$

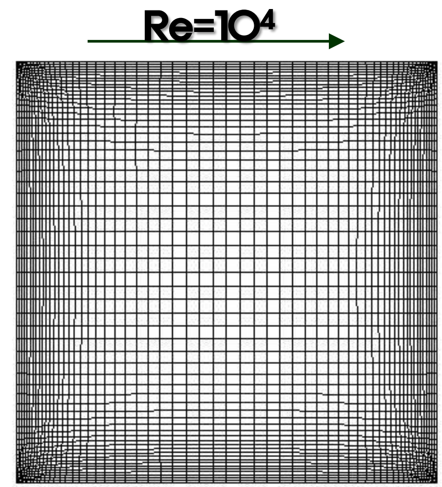
3. Continuity Equation

$$\frac{\partial}{\partial\xi}(\rho U)+\frac{\partial}{\partial\eta}(\rho V)+\frac{\partial}{\partial\phi}(\rho W)=0$$

4. Total Enthalpy

$$H=E+p$$
$$=\rho\left(e+\frac{1}{2}\left[u^2+v^2+w^2\right]\right)+p$$

hFlow™(Code Validation for Convection Scheme)



1. Validation from

- U. Ghia, K. N. Ghia, and C. T. Shin(1982)

2. Boundary condition

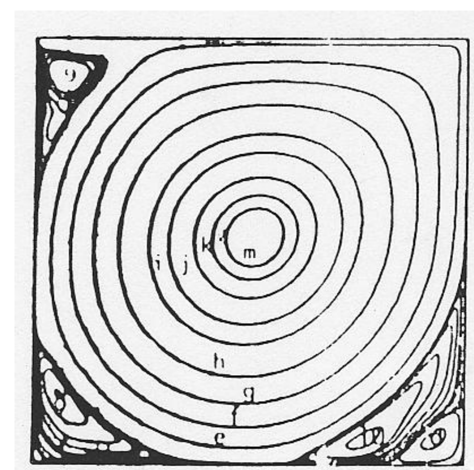
- Lid driven cavity
- Re=10^4

3. Numerical scheme

Convection scheme	- 1st Order Upwind - 2nd Order Upwind - QUICK
Flux splitting scheme	- Liou et al. (1990)
Pressure & velocity linkage	- SIMPLE

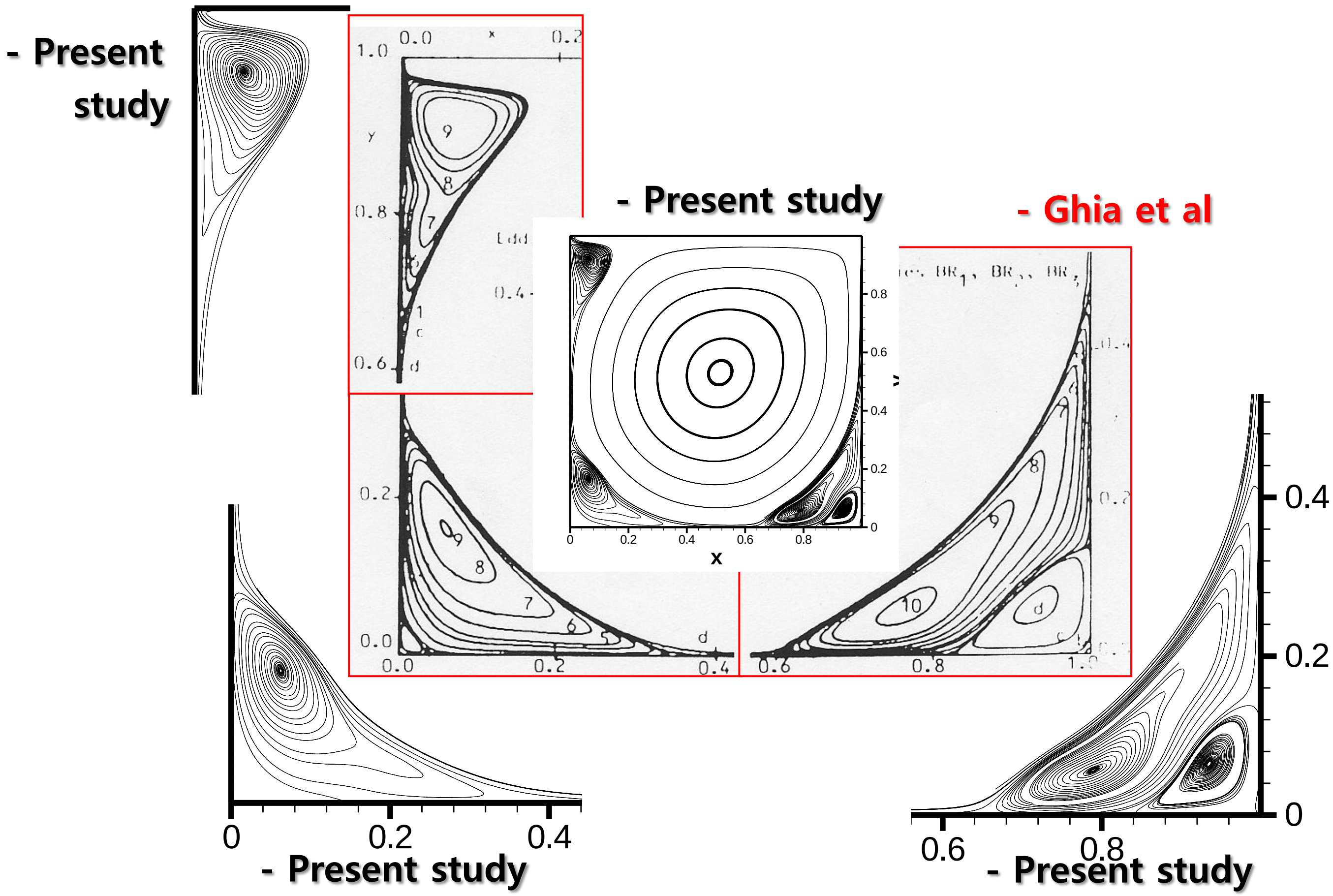
4. Mesh generation

- Numerical mesh(80 by 80)



5. Streamline from Ghia et al.

hFlow™(Code Validation for Convection Scheme)



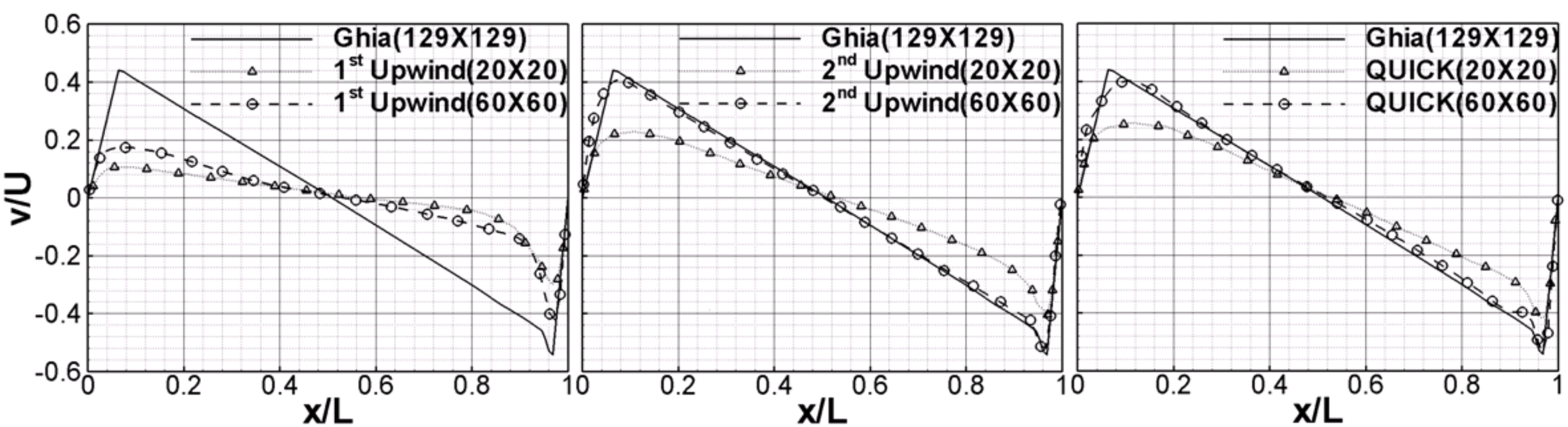
1. Comparison of streamline pattern.

- Present study : QUICK
- Ghia et al. : 3rd order upwind

hFlow™(Code Validation for Convection Scheme)

1. Vertical velocity distribution comparison of present study results with those of Ghia et al.* at the mid-height of lid driven square cavity for various convection scheme and mesh size.

*** U. Ghia, K. N. Ghia, and C. T. Shin, "High-Re solutions for incompressible flow using the Navier-Stokes equations and a multigrid method," J. Compt. Phys. 48, 387, (1982).**



2. 1st order upwind **3. 2nd order upwind** **4. QUICK**

III. Turbulence Scheme
– hFlow –

hFlow™(Turbulence Flow Analysis Code)

1. Turbulence Kinetic Energy and Dissipation Rate Equation

$$\frac{\partial \rho\Phi}{\partial t}+\frac{\partial}{\partial \xi}(\rho U\Phi)+\frac{\partial}{\partial \eta}(\rho V\Phi)+\frac{\partial}{\partial \phi}(\rho W\Phi)=\frac{\partial}{\partial \xi}\left[\frac{\Gamma_\Phi}{J}\left(q_{11}\frac{\partial \Phi}{\partial \xi}+q_{12}\frac{\partial \Phi}{\partial \eta}+q_{13}\frac{\partial \Phi}{\partial \phi}\right)\right]$$
$$+\frac{\partial}{\partial \eta}\left[\frac{\Gamma_\Phi}{J}\left(q_{21}\frac{\partial \Phi}{\partial \xi}+q_{22}\frac{\partial \Phi}{\partial \eta}+q_{23}\frac{\partial \Phi}{\partial \phi}\right)\right]$$
$$+\frac{\partial}{\partial \phi}\left[\frac{\Gamma_\Phi}{J}\left(q_{31}\frac{\partial \Phi}{\partial \xi}+q_{32}\frac{\partial \Phi}{\partial \eta}+q_{33}\frac{\partial \Phi}{\partial \phi}\right)\right]$$
$$+R_1+R_2$$

2. For Turbulence Kinetic Energy Equation

$$R_1=\Pi \qquad R_2=-\rho\varepsilon=-\left(\frac{C_\mu \rho^2 k^*}{\mu_t}\right)k$$

3. For Turbulence Dissipation Rate Equation

$$\mathrm{R}_1=\frac{C_1\varepsilon\,\Pi}{\mathrm{k}} \qquad \mathrm{R}_2=C_2\rho\frac{\varepsilon^2}{k}=-\left(\frac{C_2\rho\varepsilon^*}{k^*}\right)\varepsilon$$

4. Production and eddy viscosity

$$\Pi=\tau_{ij}\frac{\partial\langle u_i\rangle}{\partial x_j}=\left[\mu_t\left(\frac{\partial\langle u_i\rangle}{\partial x_j}+\frac{\partial\langle u_j\rangle}{\partial x_i}\right)-p\delta_{ij}\right]\frac{\partial\langle u_i\rangle}{\partial x_j} \qquad \mu_t=\frac{C_\mu f_\mu \rho k^2}{\varepsilon}$$

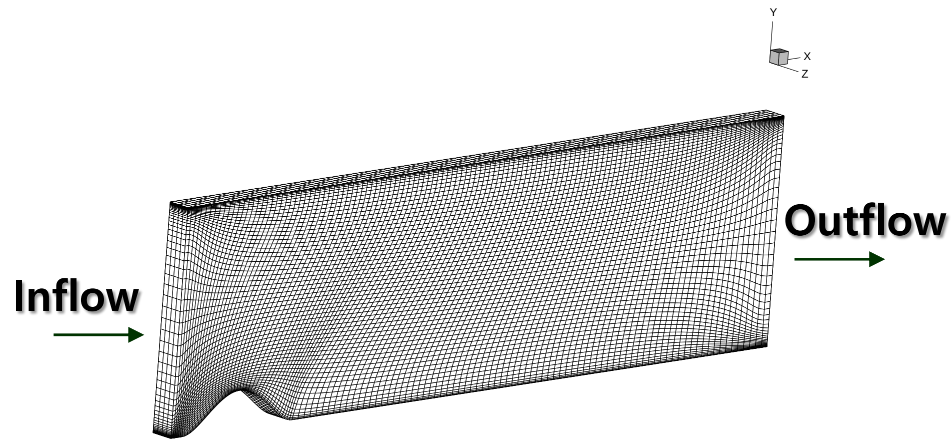
hFlow™(Code Validation for Turbulence Scheme)

1. Validation from

- G. P. Almeida, D. F. G. Durao, M. V. Heitor
Wake Flows Behind Two-Dimensional Model Hills
Experimental Thermal and Fluid Science, Vol. 7, pp. 87-101, 1993

2. Calculation Conditions

Re	=	6×10^6
Tu_∞	=	3 %
U_o	=	2.147 m/s
R	=	56 mm
h	=	28 mm

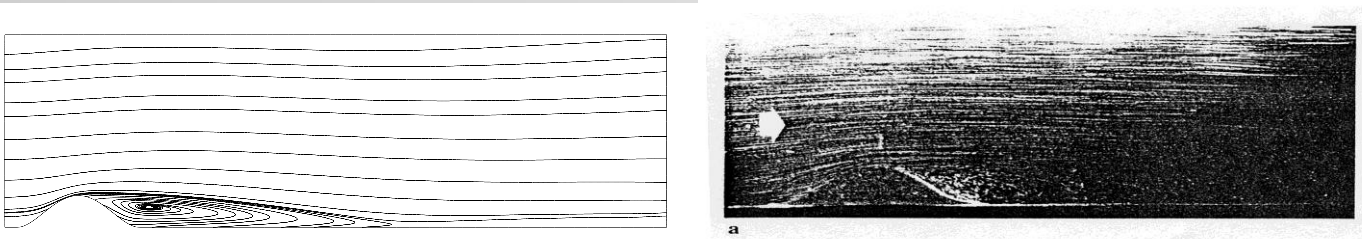


4. Mesh generation

3. Numerical Scheme

Convection Scheme	- 2^{nd} Order Upwind
Flux Splitting Scheme	- Liou et al. (1990)
Pressure & Velocity Linkage	-SIMPLE
Turbulence Model	- k-w (Wilcox, 1994)

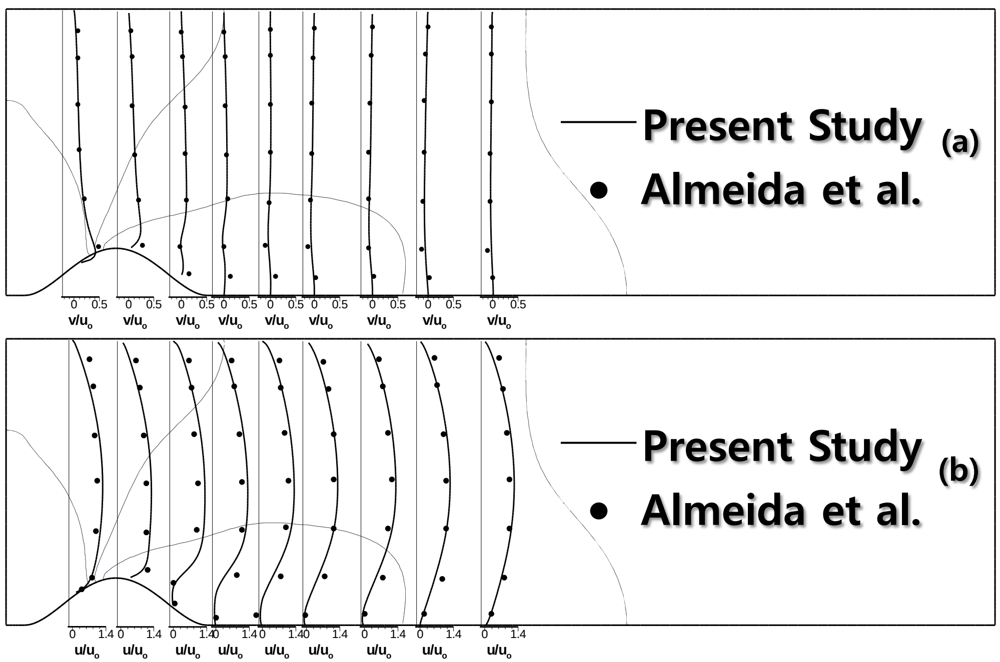
hFlow™(Code Validation for Turbulence Scheme)



(a) (b)

1. Field distribution of streamlines for a single hill.

(a) Numerical Calculation (b) Experimental Result



2. Vertical profiles of mean velocity characteristics over a single hill.

(a) Mean vertical velocity, U/U_o (b) mean horizontal velocity, V/U_o

IV. Stress Analysis
-sFlow-

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sFlow™(Stress Analysis Code)

1. Equilibrium Equation

$$(\lambda+G)\frac{\partial}{\partial x}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right)+G\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial_2 w}{\partial z^2}\right)=\frac{\alpha E}{1-2\nu}\frac{\partial T}{\partial x}-X$$

2. Elastic Modulus

$$G=\frac{E}{2(1+\nu)} \qquad \lambda=\frac{\nu E}{(1+\nu)(1-2\nu)}$$

3. Constitutive Equation

$$\varepsilon_x=\frac{\partial u}{\partial x} \qquad \varepsilon_y=\frac{\partial v}{\partial y} \qquad \varepsilon_z=\frac{\partial w}{\partial z} \qquad e=\varepsilon_x+\varepsilon_y+\varepsilon_z$$

$$\gamma_{xy}=\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x} \qquad \gamma_{xz}=\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x} \qquad \gamma_{yz}=\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y} \qquad \gamma_{xy}=\frac{1}{G}\tau_{xy} \qquad \gamma_{yz}=\frac{1}{G}\tau_{yz} \qquad \gamma_{zx}=\frac{1}{G}\tau_{zx}$$

$$\sigma_x=\frac{\nu E}{(1+\nu)(1-2\nu)}e+\frac{E}{1+\nu}\varepsilon_x \qquad \sigma_y=\frac{\nu E}{(1+\nu)(1-2\nu)}e+\frac{E}{1+\nu}\varepsilon_y \qquad \sigma_z=\frac{\nu E}{(1+\nu)(1-2\nu)}e+\frac{E}{1+\nu}\varepsilon_z$$

4. Principal Stress

$$\sigma^3-I_1\sigma^2+I_2\sigma-I_3=0$$

5. Invariant

$$I_1=\sigma_x+\sigma_y+\sigma_z=\sigma_1+\sigma_2+\sigma_3$$

$$I_2=\sigma_y\sigma_z+\sigma_z\sigma_x+\sigma_x\sigma_y-\tau_{yz}^2-\tau_{xz}^2-\tau_{xz}^2=\sigma_2\sigma_3+\sigma_3\sigma_1+\sigma_1\sigma_2$$

$$I_3=\begin{vmatrix}\sigma_x & \tau_{yx} & \tau_{zx}\\ \tau_{xy} & \sigma_y & \tau_{zy}\\ \tau_{xz} & \tau_{yz} & \sigma_z\end{vmatrix}=\sigma_1\sigma_2\sigma_3$$

6. Failure criteria developed by Von Mises and Hencky

$$\tau_0=\left(\frac{1}{9}\left[(\sigma_x-\sigma_y)^2+(\sigma_y-\sigma_z)^2+(\sigma_z-\sigma_x)^2+6\tau_{xy}^2+6\tau_{xz}^2+6\tau_{yz}^2\right]\right)^{1/2}$$

$$=\frac{\sqrt{2}}{3}Y$$

- Y : Tensile yield stress of the material as determined from a standard tension test

sFlow™(Code Validation for Stress Analysis)

1. Validation from

- In plate with a circular hole, Timoshenko and Goodier(1970)

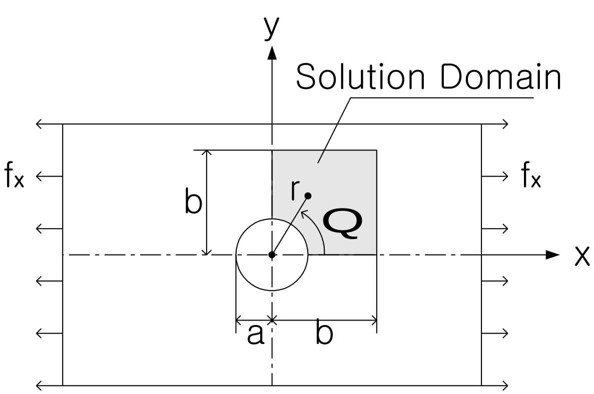
$$\sigma_{xx} = f_x\left[1-\frac{a^2}{r^2}\left(\frac{3}{2}\cos 2\theta+\cos 4\theta\right)+\frac{3}{2}\frac{a^4}{r^4}\cos 4\theta\right]$$

$$\sigma_{yy} = f_x\left[-\frac{a^2}{r^2}\left(\frac{1}{2}\cos 2\theta-\cos 4\theta\right)-\frac{3}{2}\frac{a^4}{r^4}\cos 4\theta\right]$$

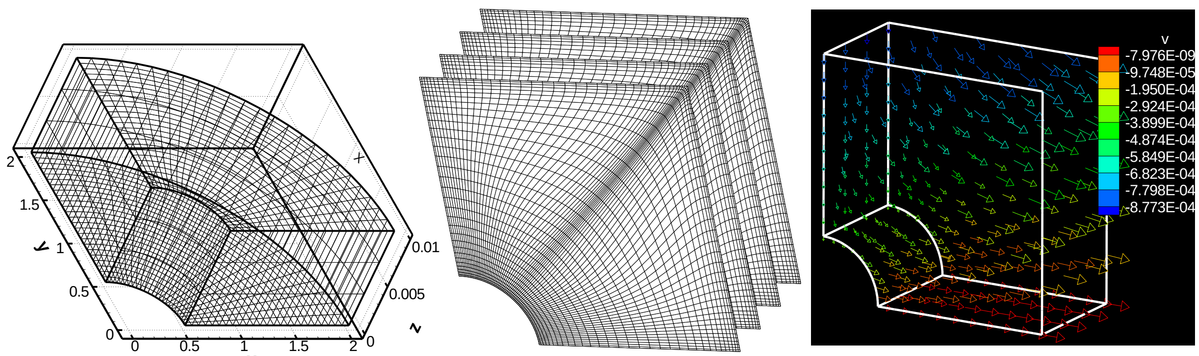
$$\sigma_{xy} = f_x\left[-\frac{a^2}{r^2}\left(\frac{1}{2}\sin 2\theta+\sin 4\theta\right)+\frac{3}{2}\frac{a^4}{r^4}\sin 4\theta\right]$$

2. Calculation Conditions

f_x = 10^4 Pa
E = 10^7 Pa
a = 0.5 m
b = 2 m
ν = 0.3



3. Schematic diagram of Calculation domain.

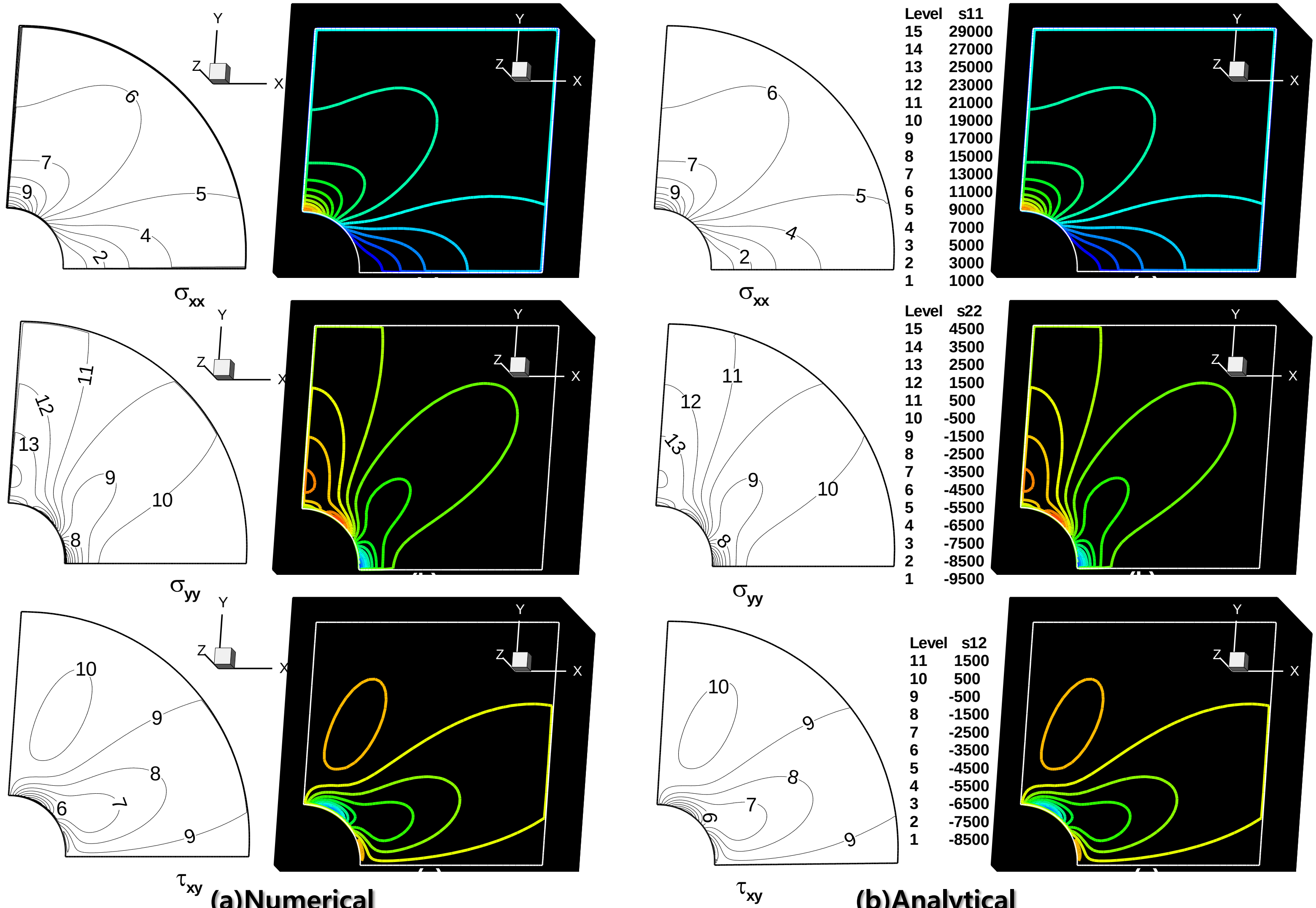


(a) (b) (c)

4. Computational mesh and displacement vector distribution.

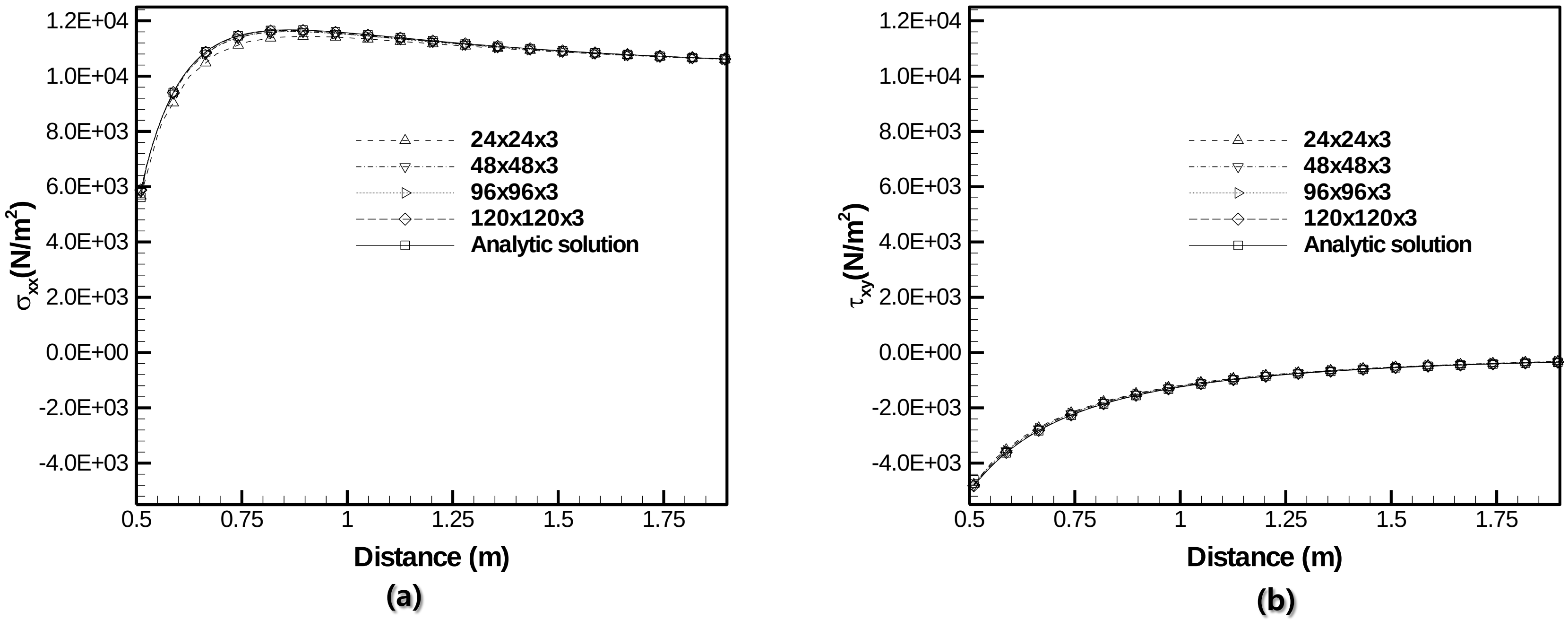
(a)Round edge, (b)Rectangular edge, (c)Displacement vector

sFlow™(Code Validation for Stress Analysis)



1. Comparison of (a)numerical and (b)analytical principal stress fields.

sFlow™(Code Validation for Stress Analysis)



1. Comparison of numerical and analytical stress distributions at θ=45° with grid dependency.

(a) x direction normal stress, (b) shear stress

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