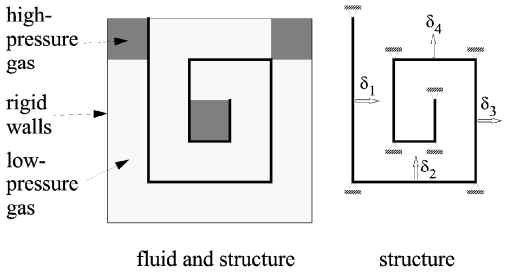
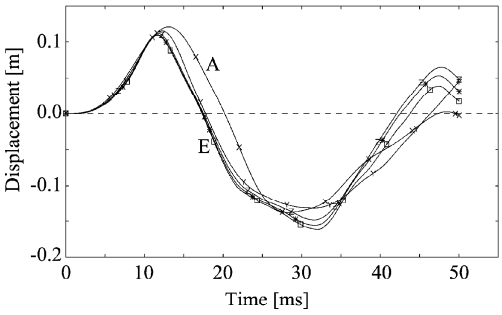
Example 4b – Explosions in a labyrinth





Labyrinth: displacement δ_i in cases A to E (progressive mesh refinement)

Case	Mesh refinement Φ (F/S)	Number of elements (F/S)	Time steps	CPU time [s]	CPU time ratio	Speed-up factor
A	1x/1x	100/32	1050	2.6	1.0	-
B	2x/2x	400/64	2100	11.7	4.5	-
C	4x/4x	1600/128	4200	77.5	29.8	-
D	8x/8x	6400/256	8400	587.3	225.9	-
E	16x/16x	25600/512	16789	4747.7	1826.0	-
F	8x/1x	6400/32	1416	110.1	42.3	5.3
G	16x/2x	25600/64	3063	933.7	359.1	5.1
H	16x/1x	25600/32	3087	960.2	369.3	4.9

23

Geometric data and materials:

The box is 5 units wide and 5 units high. The bubbles are square in shape and have unit sides. The external walls are rigid and the internal structure is deformable.

The fluids are perfect gases. The structure is steel with an elasto-plastic law.

Numerical Solutions

LABI01 (A)

This model uses conforming FSI. The fluid mesh 100 elements only and the structure is discretized by 32 elements of the ED01 type.

The mesh generation file is:

```
*%siz 4000
opti echo 1;
opti titr 'LABI - 01';
opti sauv form 'labi01.msh';
opti trac psc ftra 'labi01_mesh.ps';
opti dime 2 elem qua4;

tol = 0.01;
ns = 2;
nf = 2;

up    =  0  1;
down  =  0 -1;
right =  1  0;
left  = -1  0;

ps1 = 1 5;
ps2 = 1 1;
ps3 = 4 1;
ps4 = 4 4;
ps5 = 2 4;
ps6 = 2 2 ;
ps7 = 3 2;
ps8 = 3 3;
stru1 = ps1 d (ns * 4) ps2;
stru2 = ps2 d (ns * 3) ps3;
stru3 = ps3 d (ns * 3) ps4;
stru4 = ps4 d (ns * 2) ps5;
stru5 = ps5 d (ns * 2) ps6;
stru6 = ps6 d (ns * 1) ps7;
stru7 = ps7 d (ns * 1) ps8;
stru = stru1 et stru2 et stru3 et stru4 et stru5 et stru6 et stru7;
trac qual stru;

pf1 = 1 5;
pf2 = 0 5;
c1 = pf1 d nf pf2;
flu1 = c1 tran nf down;
flu2 = flu1 plus down;
elim tol (flu1 et flu2);
flu3 = flu2 plus down;
elim tol (flu2 et flu3);
flu4 = flu3 plus down;
elim tol (flu3 et flu4);
flu5 = flu4 plus down;
elim tol (flu4 et flu5);
flu6 = flu5 plus right;
elim tol (flu5 et flu6);
flu7 = flu6 plus right;
elim tol (flu6 et flu7);
flu8 = flu7 plus right;
elim tol (flu7 et flu8);
flu9 = flu8 plus right;
elim tol (flu8 et flu9);
flu10 = flu9 plus up;
elim tol (flu9 et flu10);
flu11 = flu10 plus up;
elim tol (flu10 et flu11);
flu12 = flu11 plus up;
elim tol (flu11 et flu12);
flu13 = flu12 plus up;
elim tol (flu12 et flu13);
flu14 = flu13 plus left;
elim tol (flu13 et flu14);
flu15 = flu14 plus left;
elim tol (flu14 et flu15);
```

```
flu16 = flu15 plus left;
elim tol (flu15 et flu16);
flu17 = flu16 plus down;
elim tol (flu16 et flu17);
flu18 = flu17 plus down;
elim tol (flu17 et flu18);
flu19 = flu18 plus down;
elim tol (flu18 et flu19);
flu20 = flu19 plus right;
elim tol (flu19 et flu20);
flu21 = flu20 plus right;
elim tol (flu20 et flu21);
flu22 = flu21 plus up;
elim tol (flu21 et flu22);
flu23 = flu22 plus up;
elim tol (flu22 et flu23);
flu24 = flu23 plus left;
elim tol (flu23 et flu24);
flu25 = flu24 plus down;
elim tol (flu24 et flu25);

expl = flu1 et flu13 et flu25;
gas = flu2 et flu3 et flu4 et flu5 et
      flu6 et flu7 et flu8 et flu9 et flu10 et
      flu11 et flu12 et flu14 et flu15 et
      flu16 et flu17 et flu18 et flu19 et flu20 et
      flu21 et flu22 et flu23 et flu24;
flui = expl et gas;
trac qual flui;

coco = cont flui;

d1 = stru poin proc (1 3);
d2 = stru poin proc (2.5 1);
d3 = stru poin proc (4 2.5);
d4 = stru poin proc (3 4);
tpln = d1 et d2 et d3 et d4;
pe1 = 0 5;
pe2 = 0 0;
pe3 = 5 0;
pe4 = 5 5;
pe5 = 1 5;
pe6 = 1 1;
pe7 = 2 2;
```

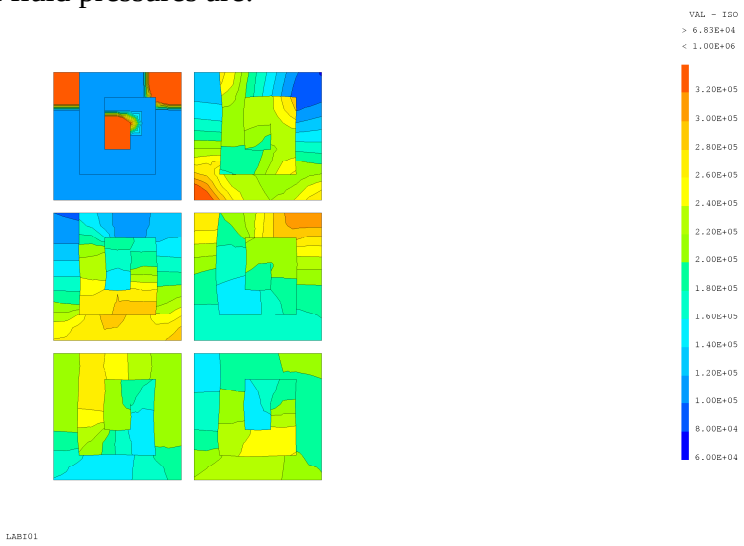
```
e1 = flu1 elem cont (flu1 poin proc pe1);
e2 = flu5 elem cont (flu5 poin proc pe2);
e3 = flu9 elem cont (flu9 poin proc pe3);
e4 = flu13 elem cont (flu13 poin proc pe4);
e5 = flu16 elem cont (flu16 poin proc pe5);
e6 = flu19 elem cont (flu19 poin proc pe6);
e7 = flu25 elem cont (flu25 poin proc pe7);
tple = e1 et e2 et e3 et e4 et e5 et e6 et e7;
trac qual (coco et tple et tpln);
*opti trac mif;
*trac qual (coco et tple et tpln);

*fsan = (flu1 et flu2 et flu3 et flu4) poin droi p1s p2s tol;
*fsan = fsan et
*       ((flu16 et flu17 et flu18 et flu19) poin droi p1s p2s tol);
*fsan = fsan et ((flu6 et flu7 et flu8) poin droi p2s p3s tol);
*fsan = fsan et ((flu19 et flu20 et flu21) poin droi p2s p3s tol);
*fsan = fsan et ((flu10 et flu11 et flu12) poin droi p3s p4s tol);
*fsan = fsan et ((flu21 et flu22 et flu23) poin droi p3s p4s tol);
fsan = cont flui;
fsan = chan poi1 fsan;
fsrn = flui poin droi pe1 pe2 tol;
fsrn = fsrn et (flui poin droi pe2 pe3 tol);
fsrn = fsrn et (flui poin droi pe3 pe4 tol);
fsrn = fsrn et (flui poin droi pe4 pe1 tol);
fsrn = chan poi1 fsrn;
fsan = fsan diff (fsan inte fsrn);
trac fsan;
trac fsrn;
bloc = ps1 et ps2 et ps3 et ps4 et ps5 et ps6 et ps7 et ps8;

mesh = flui et stru et fsan et fsrn et tple et tpln et bloc;
tass mesh;
sauv form mesh;
list (nbno flui);
list (nbno stru);
list (nbno fsan);
list (nbno fsrn);
list (nbel flui);
list (nbel stru);
opti trac mif;
trac stru;
trac (cont flui);
fin;
```

The input file is:

```
LABI01
ECHO
*CONV win
CAST mesh
DPLA ALE
DIME
  NALE 21 NBLE 1
  BLOQ 1200
  FSA 75 IFSA 202
  LIAI 358
  ndvc 196
TERM
GEOM FL24 flui ED01 stru TERM
COMP EPAI 0.01 LECT stru TERM
GRIL LAGR LECT stru TERM
     EULE LECT fsrn fsan TERM
     MEAN AUTR
OPTI REZO MVRE MODU LIAI
MATE VM23 RO 8000 YOUNG 2.E11 NU 0.3 ELAS 4.E8
          TRAC 3 4.E8 2.E-3 2.4E9 1.002E0 2.4E9 10.
          LECT stru TERM
     FLUT RO 10. EINT 2.5E5 GAMM 1.4 PB 0 ITER 1 ALF0 1
          BET0 1 KINT 1 AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1
          pref 1.e5
          LECT expl TERM
     FLUT RO  1. EINT 2.5E5 GAMM 1.4 PB 0 ITER 1 ALF0 1
          BET0 1 KINT 1 AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1
          pref 1.e5
          LECT gas TERM
LIAI freq 1
     BLOQ 123 LECT bloc TERM
     FSR LECT fsrn TERM
     FSA LECT fsan TERM
ECRI DEPL VITE ECRO TFRE 10.E-3
     POIN LECT tpln TERM
     ELEM LECT tple TERM
     TRAC TPLO DESC 'LABI01' TFRE 51.E-6
               POIN LECT tpln TERM
               ELEM LECT tple TERM
     fich alic temp TFRE 51.E-6
               POIN LECT tpln TERM
               ELEM LECT tple TERM
```

```
     FICH FORM K200 TFRE 2.E-3
          POIN TOUS
          VARI DEPL VITE ECRO ECRC LECT 1 3 TERM
OPTI NOTE
  CSTA 0.5D0
* MOMT 2
  FSCR
  LOG 1
CALCUL TINI 0. TEND 50.E-3
*
SUIT
Post-treatment
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR  1 'dx_1'  DEPL COMP 1 POIN LECT d1 TERM
COUR  2 'dy_2'  DEPL COMP 2 POIN LECT d2 TERM
COUR  3 'dx_3'  DEPL COMP 1 POIN LECT d3 TERM
COUR  4 'dy_4'  DEPL COMP 2 POIN LECT d4 TERM
COUR  5 'p_e1'  ECRO COMP 1 ELEM LECT e1 TERM
COUR  6 'p_e2'  ECRO COMP 1 ELEM LECT e2 TERM
COUR  7 'p_e3'  ECRO COMP 1 ELEM LECT e3 TERM
COUR  8 'p_e4'  ECRO COMP 1 ELEM LECT e4 TERM
COUR  9 'p_e5'  ECRO COMP 1 ELEM LECT e5 TERM
COUR 10 'p_e6'  ECRO COMP 1 ELEM LECT e6 TERM
COUR 11 'p_e7'  ECRO COMP 1 ELEM LECT e7 TERM
*
trac 1 2 3 4 axes 1.0 'D [M]'
trac 5 6 7 8 axes 1.0 'P [PA]'
trac 9 10 11 axes 1.0 'P [PA]'
LIST 1 2 3 4 axes 1.0 'D [M]'
LIST 5 6 7 8 axes 1.0 'P [PA]'
LIST 9 10 11 axes 1.0 'P [PA]'
*
*QUAL VITE comp 1 lect 51 term REFE 8.25539E+2 TOLE 5.E-3
*     ECRO comp 1 lect 50 term REFE 3.41392E+5 TOLE 5.E-3
FIN
```

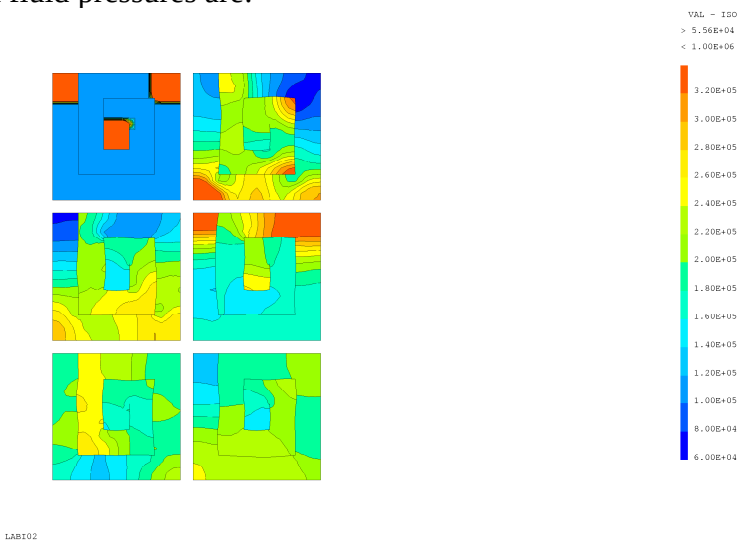
The computed fluid pressures are:



LABI02 (B)

Twice finer conforming FSI solution. The fluid mesh uses 400 elements and the structure is discretized by 64 elements of the ED01 type.

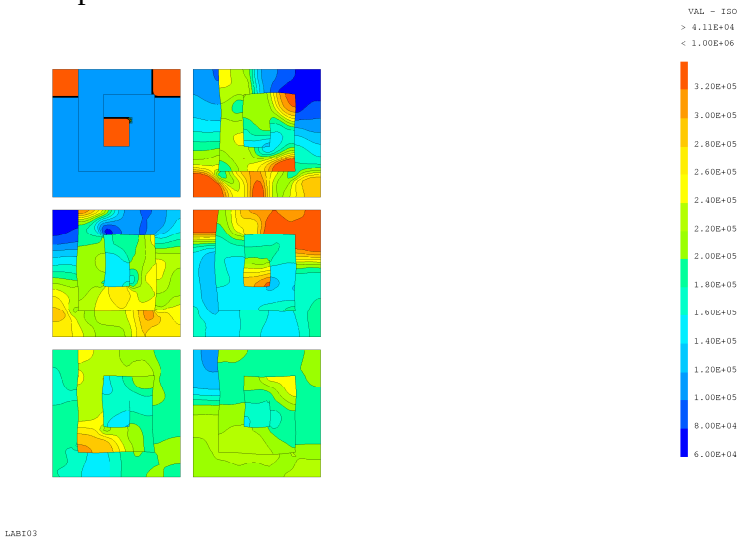
The computed fluid pressures are:



LABI03 (C)

Four-times finer conforming FSI solution. The fluid mesh uses 1600 elements and the structure is discretized by 128 elements of the ED01 type.

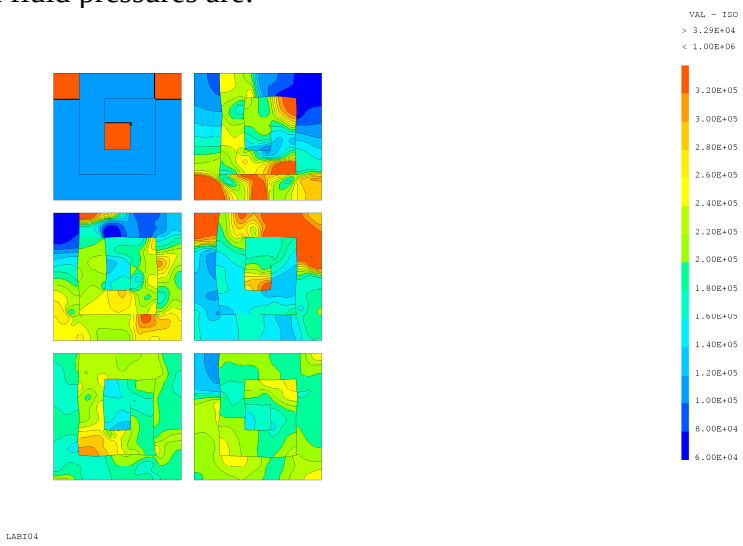
The computed fluid pressures are:



LABI04 (D)

Eight-times finer conforming FSI solution. The fluid mesh uses 6400 elements and the structure is discretized by 256 elements of the ED01 type.

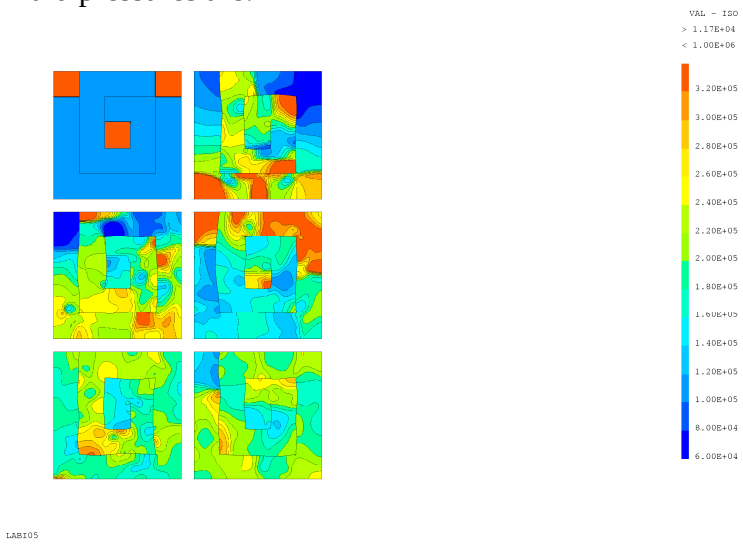
The computed fluid pressures are:



LABI05 (E)

Sixteen-times finer conforming FSI solution. The fluid mesh uses 25600 elements and the structure is discretized by 512 elements of the ED01 type.

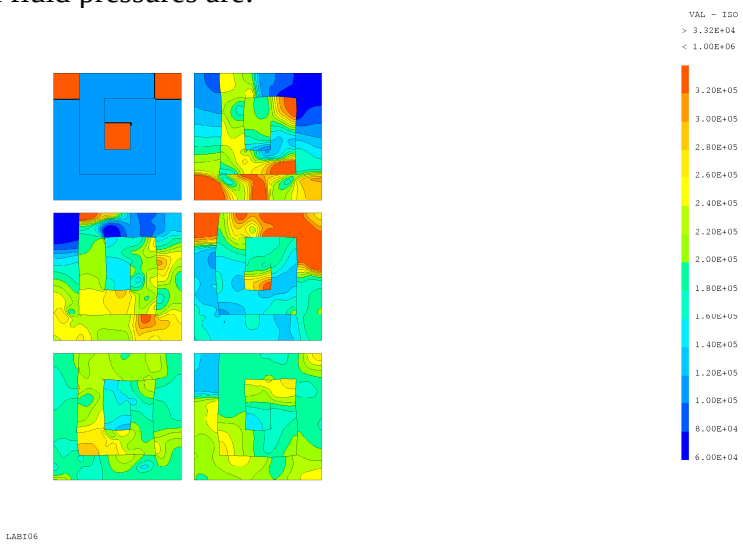
The computed fluid pressures are:



LABI06 (F)

Eight-times finer non-conforming FSI solution. The fluid mesh uses 6400 elements and the structure is discretized by 32 elements of the ED01 type.

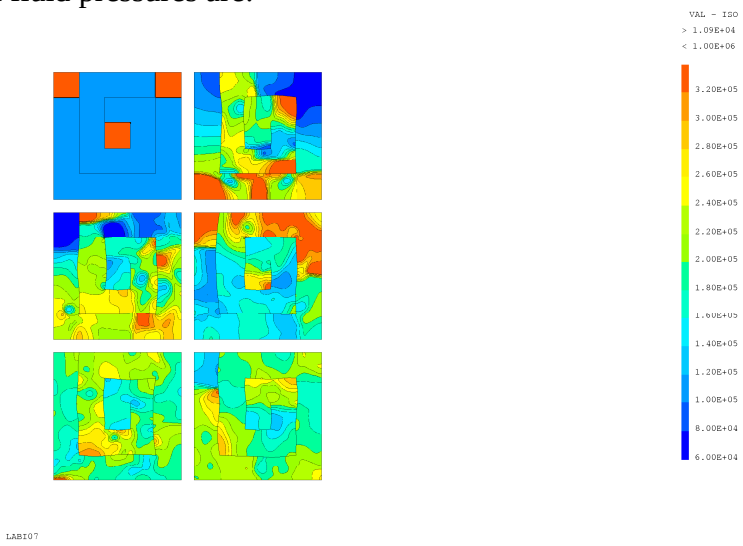
The computed fluid pressures are:



LABI07 (G)

Sixteen-times (two time in the structure) finer non-conforming FSI solution. The fluid mesh uses 25600 elements and the structure is discretized by 64 elements of the ED01 type.

The computed fluid pressures are:



LABI08 (H)

Sixteen-times finer non-conforming FSI solution. The fluid mesh uses 25600 elements and the structure is discretized by 32 elements of the ED01 type.

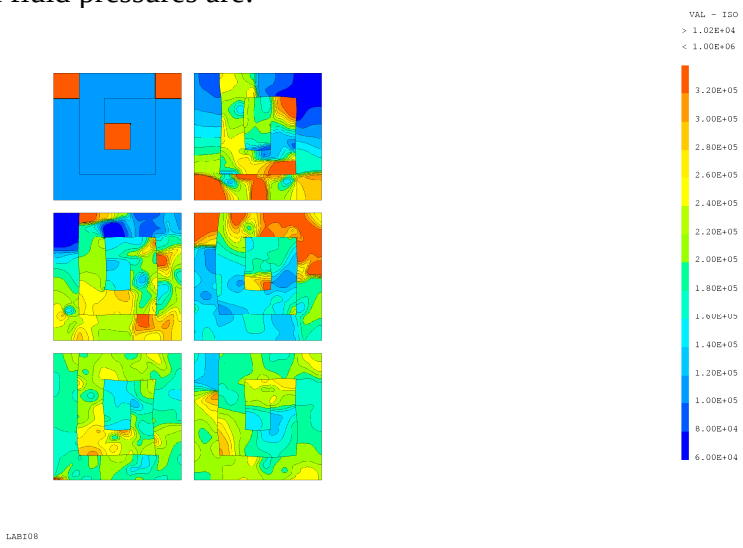
The mesh generation file is:

```
*%siz 4000
opti echo 1;
opti titr 'LABI - 08';
opti sauv form 'labi08.msh';
opti trac psc ftra 'labi08_mesh.ps';
opti dime 2 elem qua4;

tol = 0.01;
ns = 2;
nf = 32;

up    =  0  1;
down  =  0 -1;
right =  1  0;
left  = -1  0;

ps1 = 1 5;
ps2 = 1 1;
ps3 = 4 1;
ps4 = 4 4;
ps5 = 2 4;
ps6 = 2 2 ;
ps7 = 3 2;
ps8 = 3 3;
stru1 = ps1 d (ns * 4) ps2;
stru2 = ps2 d (ns * 3) ps3;
stru3 = ps3 d (ns * 3) ps4;
stru4 = ps4 d (ns * 2) ps5;
stru5 = ps5 d (ns * 2) ps6;
stru6 = ps6 d (ns * 1) ps7;
stru7 = ps7 d (ns * 1) ps8;
stru = stru1 et stru2 et stru3 et stru4 et stru5 et stru6 et stru7;
trac qual stru;

pf1 = 1 5;
pf2 = 0 5;
c1 = pf1 d nf pf2;
flu1 = c1 tran nf down;
flu2 = flu1 plus down;
elim tol (flu1 et flu2);
flu3 = flu2 plus down;
elim tol (flu2 et flu3);
flu4 = flu3 plus down;
elim tol (flu3 et flu4);
flu5 = flu4 plus down;
elim tol (flu4 et flu5);
flu6 = flu5 plus right;
elim tol (flu5 et flu6);
flu7 = flu6 plus right;
elim tol (flu6 et flu7);
flu8 = flu7 plus right;
elim tol (flu7 et flu8);
flu9 = flu8 plus right;
elim tol (flu8 et flu9);
flu10 = flu9 plus up;
elim tol (flu9 et flu10);
flu11 = flu10 plus up;
elim tol (flu10 et flu11);
flu12 = flu11 plus up;
elim tol (flu11 et flu12);
flu13 = flu12 plus up;
elim tol (flu12 et flu13);
flu14 = flu13 plus left;
elim tol (flu13 et flu14);
flu15 = flu14 plus left;
elim tol (flu14 et flu15);
flu16 = flu15 plus left;
elim tol (flu15 et flu16);
flu17 = flu16 plus down;
elim tol (flu16 et flu17);
flu18 = flu17 plus down;
elim tol (flu17 et flu18);
flu19 = flu18 plus down;
elim tol (flu18 et flu19);
flu20 = flu19 plus right;
elim tol (flu19 et flu20);
flu21 = flu20 plus right;
elim tol (flu20 et flu21);
flu22 = flu21 plus up;
elim tol (flu21 et flu22);
flu23 = flu22 plus up;
elim tol (flu22 et flu23);
flu24 = flu23 plus left;
elim tol (flu23 et flu24);
flu25 = flu24 plus down;
elim tol (flu24 et flu25);

expl = flu1 et flu13 et flu25;
gas = flu2 et flu3 et flu4 et flu5 et
      flu6 et flu7 et flu8 et flu9 et flu10 et
      flu11 et flu12 et flu14 et flu15 et
      flu16 et flu17 et flu18 et flu19 et flu20 et
      flu21 et flu22 et flu23 et flu24;
flui = expl et gas;
trac qual flui;

coco = cont flui;

d1 = stru poin proc (1 3);
d2 = stru poin proc (2.5 1);
d3 = stru poin proc (4 2.5);
d4 = stru poin proc (3 4);
tpln = d1 et d2 et d3 et d4;
pe1 = 0 5;
pe2 = 0 0;
pe3 = 5 0;
pe4 = 5 5;
pe5 = 1 5;
pe6 = 1 1;
pe7 = 2 2;
e1 = flu1 elem cont (flu1 poin proc pe1);
e2 = flu5 elem cont (flu5 poin proc pe2);
e3 = flu9 elem cont (flu9 poin proc pe3);
e4 = flu13 elem cont (flu13 poin proc pe4);
e5 = flu16 elem cont (flu16 poin proc pe5);
e6 = flu19 elem cont (flu19 poin proc pe6);
e7 = flu25 elem cont (flu25 poin proc pe7);
tple = e1 et e2 et e3 et e4 et e5 et e6 et e7;
trac qual (coco et tple et tpln);
*opti trac mif;
*trac qual (coco et tple et tpln);

*fsan = (flu1 et flu2 et flu3 et flu4) poin droi p1s p2s tol;
*fsan = fsan et
*       ((flu16 et flu17 et flu18 et flu19) poin droi p1s p2s tol);
*fsan = fsan et ((flu6 et flu7 et flu8) poin droi p2s p3s tol);
*fsan = fsan et ((flu19 et flu20 et flu21) poin droi p2s p3s tol);
*fsan = fsan et ((flu10 et flu11 et flu12) poin droi p3s p4s tol);
*fsan = fsan et ((flu21 et flu22 et flu23) poin droi p3s p4s tol);
fsan = cont flui;
fsan = chan poi1 fsan;
fsrn = flui poin droi pe1 pe2 tol;
fsrn = fsrn et (flui poin droi pe2 pe3 tol);
fsrn = fsrn et (flui poin droi pe3 pe4 tol);
fsrn = fsrn et (flui poin droi pe4 pe1 tol);
fsrn = chan poi1 fsrn;
fsan = fsan diff (fsan inte fsrn);
trac fsan;
trac fsrn;
bloc = ps1 et ps2 et ps3 et ps4 et ps5 et ps6 et ps7 et ps8;

mesh = flui et stru et fsan et fsrn et tple et tpln et bloc;
tass mesh;
sauv form mesh;
list (nbno flui);
list (nbno stru);
list (nbno fsan);
list (nbno fsrn);
list (nbel flui);
list (nbel stru);
fin;
```

The input file is:

```
LABI08
ECHO
*CONV win
CAST mesh
DPLA ALE
DIME
  NALE 597 NBLE 1
  BLOQ 1200
  FSA 1035 IFSA 4042
  LIAI 7318
  ndvc 99076
TERM
GEOM FL24 flui ED01 stru TERM
COMP EPAI 0.01 LECT stru TERM
GRIL LAGR LECT stru TERM
     EULE LECT fsrn fsan TERM
     MEAN AUTR
OPTI REZO MVRE MODU LIAI
MATE VM23 RO 8000 YOUNG 2.E11 NU 0.3 ELAS 4.E8
          TRAC 3 4.E8 2.E-3 2.4E9 1.002E0 2.4E9 10.
          LECT stru TERM
     FLUT RO 10. EINT 2.5E5 GAMM 1.4 PB 0 ITER 1 ALF0 1
          BET0 1 KINT 1 AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1
          pref 1.e5
          LECT expl TERM
     FLUT RO  1. EINT 2.5E5 GAMM 1.4 PB 0 ITER 1 ALF0 1
          BET0 1 KINT 1 AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1
          pref 1.e5
          LECT gas TERM
LIAI freq 1
     BLOQ 123 LECT bloc TERM
     FSR LECT fsrn TERM
     FSA NCFS LECT fsan TERM
ECRI DEPL VITE ECRO TFRE 10.E-3
     POIN LECT tpln TERM
     ELEM LECT tple TERM
     TRAC TPLO DESC 'LABI08' TFRE 51.E-6
               POIN LECT tpln TERM
               ELEM LECT tple TERM
     fich alic temp TFRE 51.E-6
               POIN LECT tpln TERM
               ELEM LECT tple TERM
     FICH FORM K200 TFRE 2.E-3
          POIN TOUS
          VARI DEPL VITE ECRO ECRC LECT 1 3 TERM
OPTI NOTE
  CSTA 0.5D0
* MOMT 2
  FSCR
  LOG 1
CALCUL TINI 0. TEND 50.E-3
*
SUIT
Post-treatment
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR  1 'dx_1'  DEPL COMP 1 POIN LECT d1 TERM
COUR  2 'dy_2'  DEPL COMP 2 POIN LECT d2 TERM
COUR  3 'dx_3'  DEPL COMP 1 POIN LECT d3 TERM
COUR  4 'dy_4'  DEPL COMP 2 POIN LECT d4 TERM
COUR  5 'p_e1'  ECRO COMP 1 ELEM LECT e1 TERM
COUR  6 'p_e2'  ECRO COMP 1 ELEM LECT e2 TERM
COUR  7 'p_e3'  ECRO COMP 1 ELEM LECT e3 TERM
COUR  8 'p_e4'  ECRO COMP 1 ELEM LECT e4 TERM
COUR  9 'p_e5'  ECRO COMP 1 ELEM LECT e5 TERM
COUR 10 'p_e6'  ECRO COMP 1 ELEM LECT e6 TERM
COUR 11 'p_e7'  ECRO COMP 1 ELEM LECT e7 TERM
*
trac 1 2 3 4 axes 1.0 'D [M]'
trac 5 6 7 8 axes 1.0 'P [PA]'
trac 9 10 11 axes 1.0 'P [PA]'
LIST 1 2 3 4 axes 1.0 'D [M]'
LIST 5 6 7 8 axes 1.0 'P [PA]'
LIST 9 10 11 axes 1.0 'P [PA]'
*
*QUAL VITE comp 1 lect 51 term REFE 8.25539E+2 TOLE 5.E-3
*     ECRO comp 1 lect 50 term REFE 3.41392E+5 TOLE 5.E-3
FIN
```

The computed fluid pressures are:

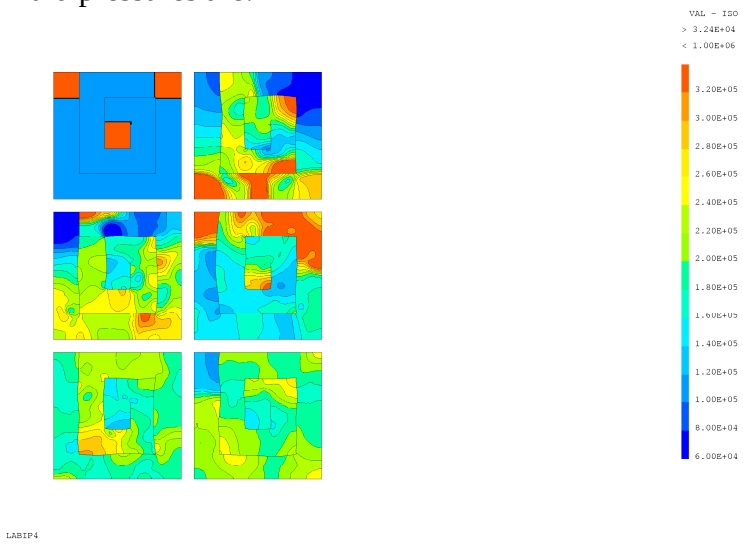


Solutions with space partitioning (OPTI PART)

LABIP4 (DP)

Eight-times finer conforming FSI solution. The fluid mesh uses 6400 elements and the structure is discretized by 256 elements of the ED01 type. Uses spatial partitioning.

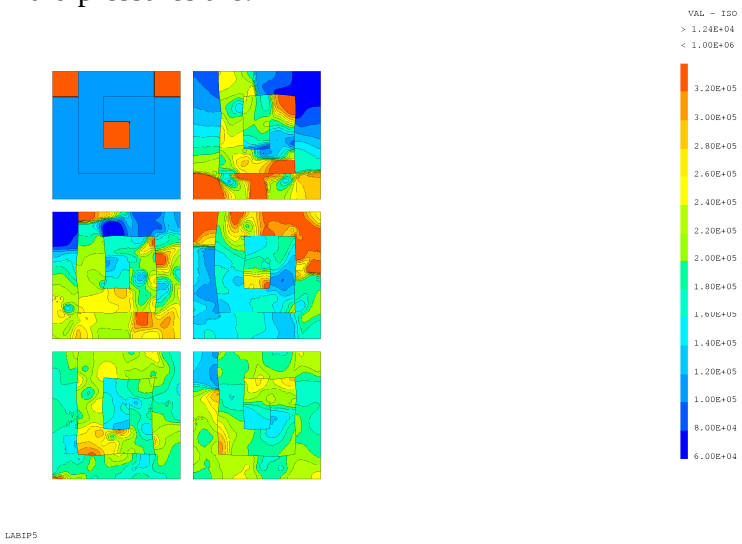
The computed fluid pressures are:



LABIP5 (EP)

Sixteen-times finer conforming FSI solution. The fluid mesh uses 25600 elements and the structure is discretized by 512 elements of the ED01 type. Uses spatial partitioning.

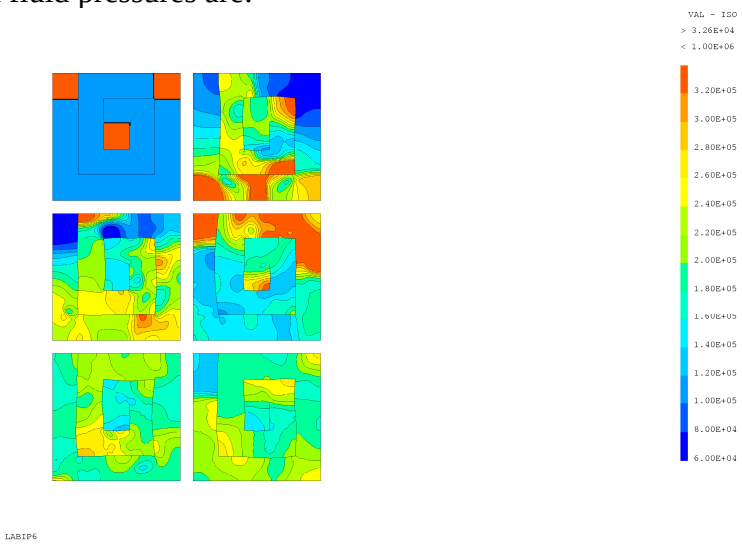
The computed fluid pressures are:



LABIP6 (FP)

Eight-times finer non-conforming FSI solution. The fluid mesh uses 6400 elements and the structure is discretized by 32 elements of the ED01 type. Uses spatial partitioning.

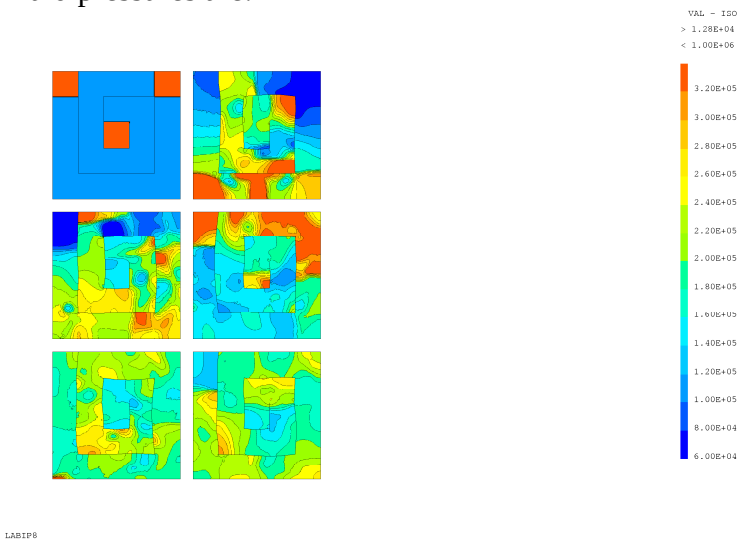
The computed fluid pressures are:



LABIP8 (HP)

Sixteen-times finer non-conforming FSI solution. The fluid mesh uses 25600 elements and the structure is discretized by 32 elements of the ED01 type. Uses spatial partitioning.

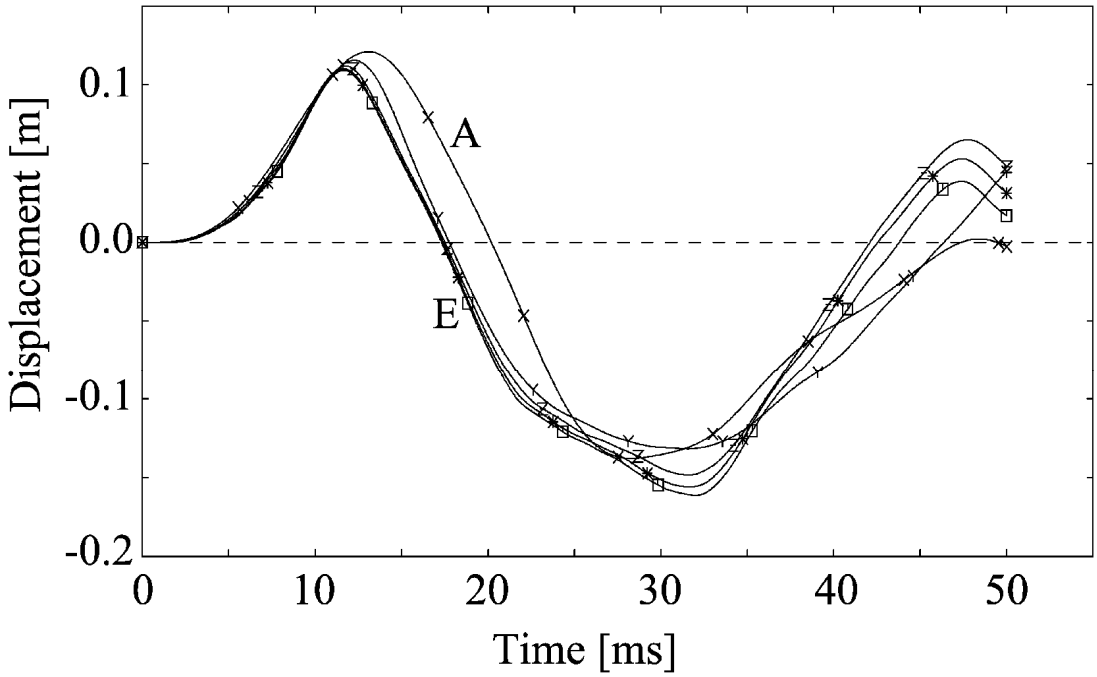
The computed fluid pressures are:



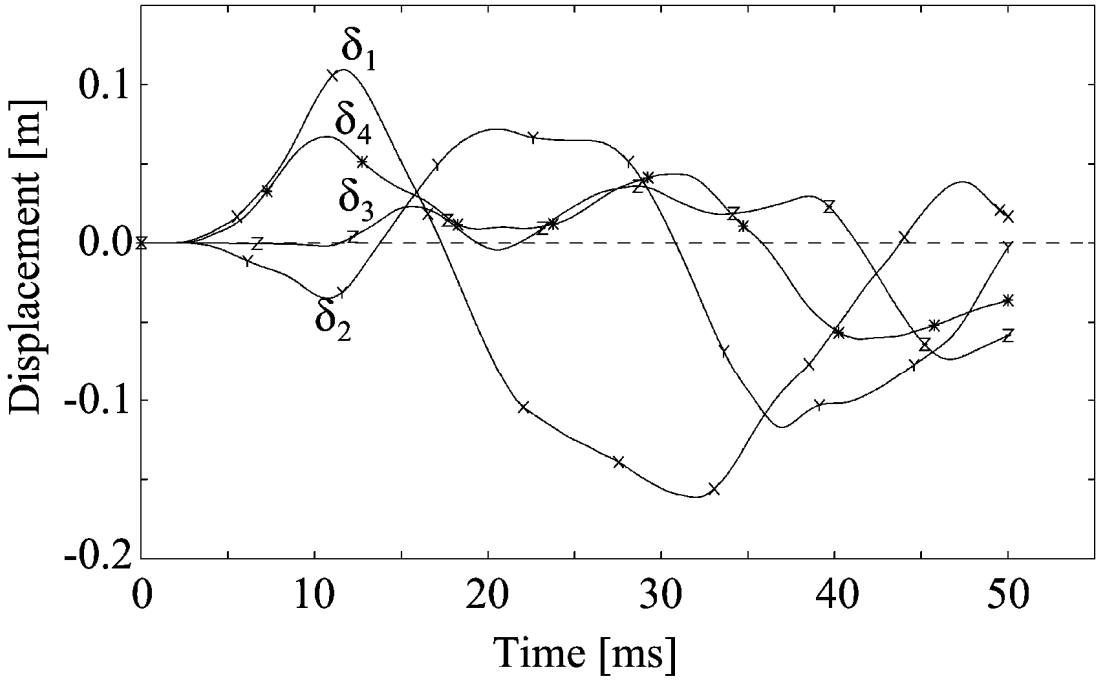
Some results comparisons

Resume of calculations (without partitioning)

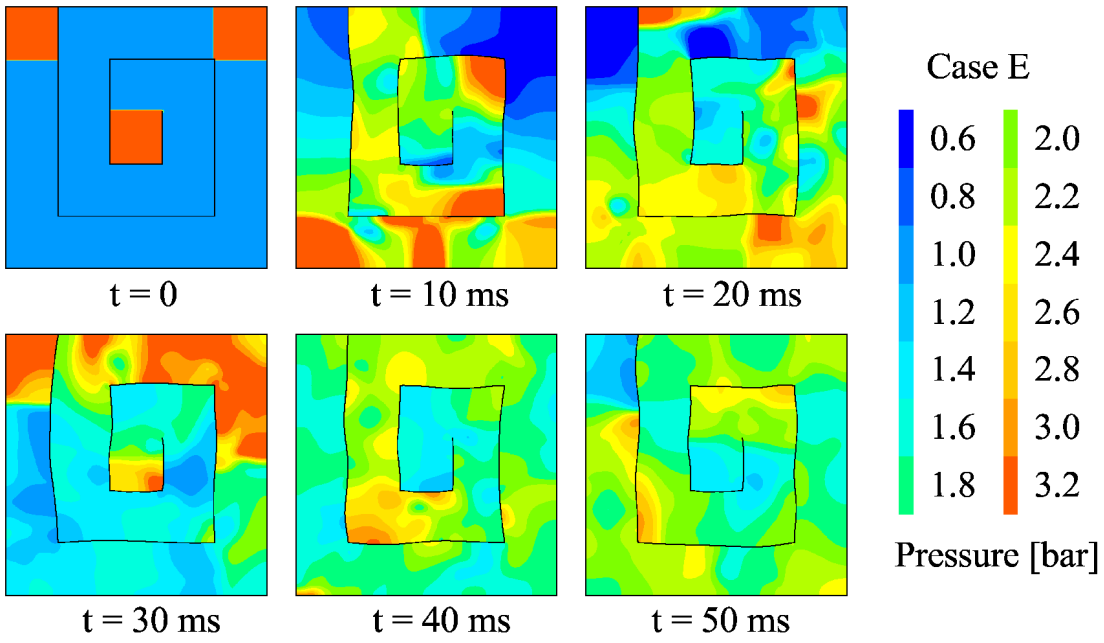
Case	Mesh refinement Φ (F/S)	Number of elements (F/S)	Time steps	CPU time [s]	CPU time ratio	Speed-up factor
A	1x/1x	100/32	1050	2.6	1.0	-
B	2x/2x	400/64	2100	11.7	4.5	-
C	4x/4x	1600/128	4200	77.5	29.8	-
D	8x/8x	6400/256	8400	587.3	225.9	-
E	16x/16x	25600/512	16789	4747.7	1826.0	-
F	8x/1x	6400/32	1416	110.1	42.3	5.3
G	16x/2x	25600/64	3063	933.7	359.1	5.1
H	16x/1x	25600/32	3087	960.2	369.3	4.9



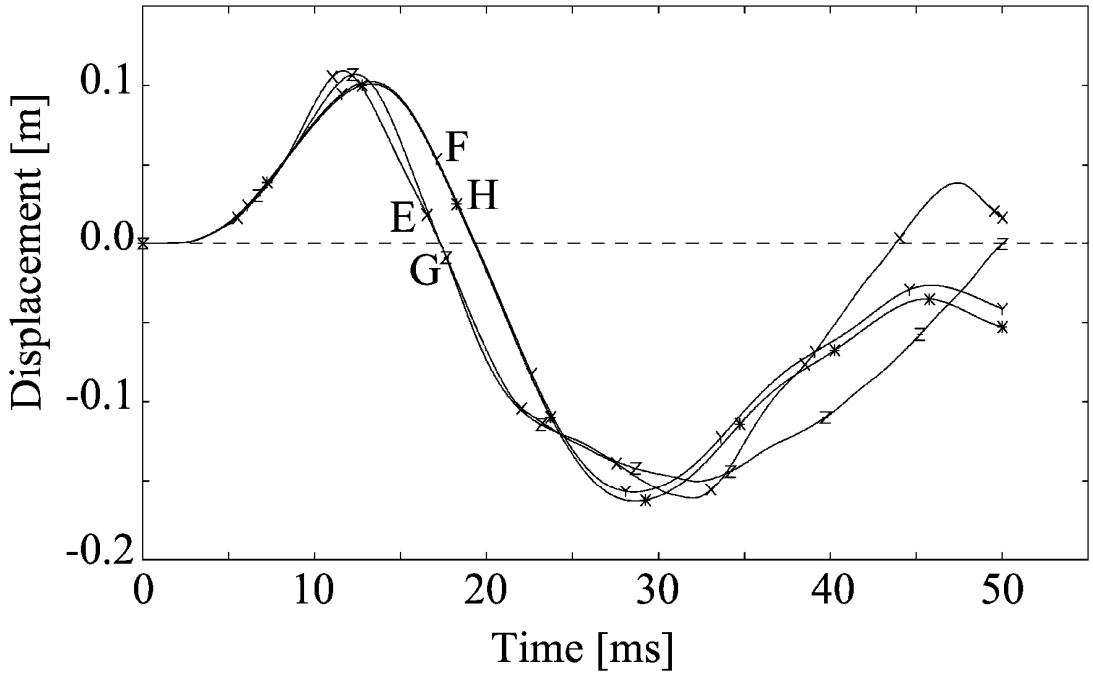
Labyrinth: displacement δ_1 in cases A to E (progressive mesh refinement)



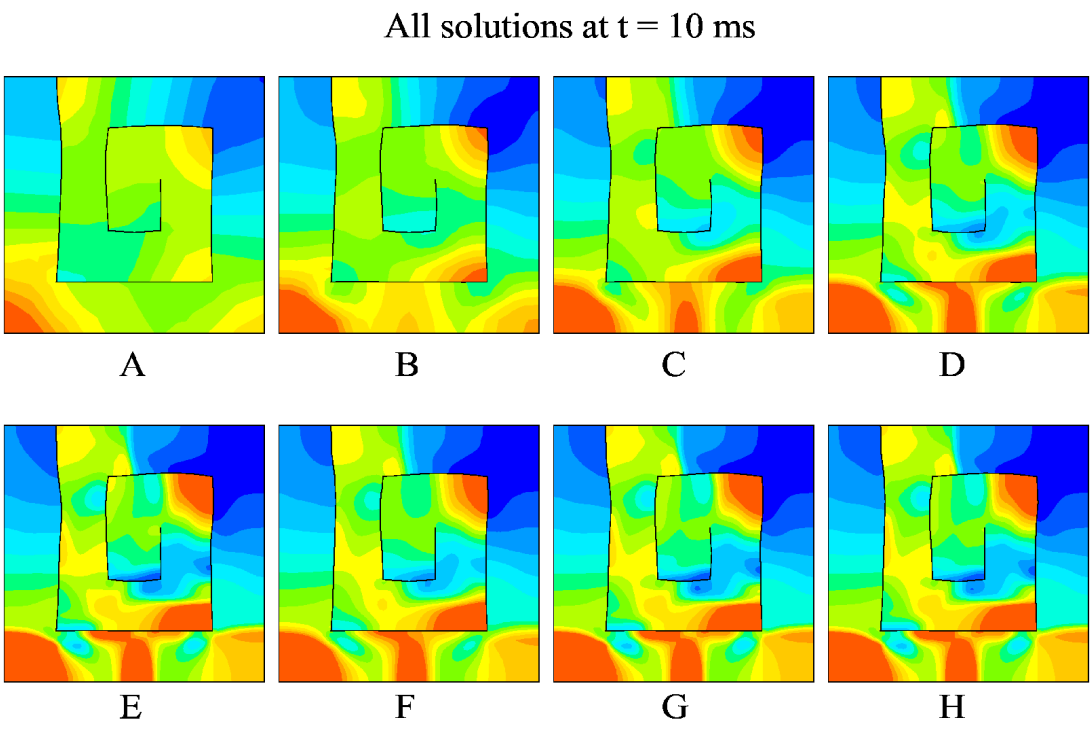
Labyrinth: displacements δ_1 to δ_4 in case E (reference solution)



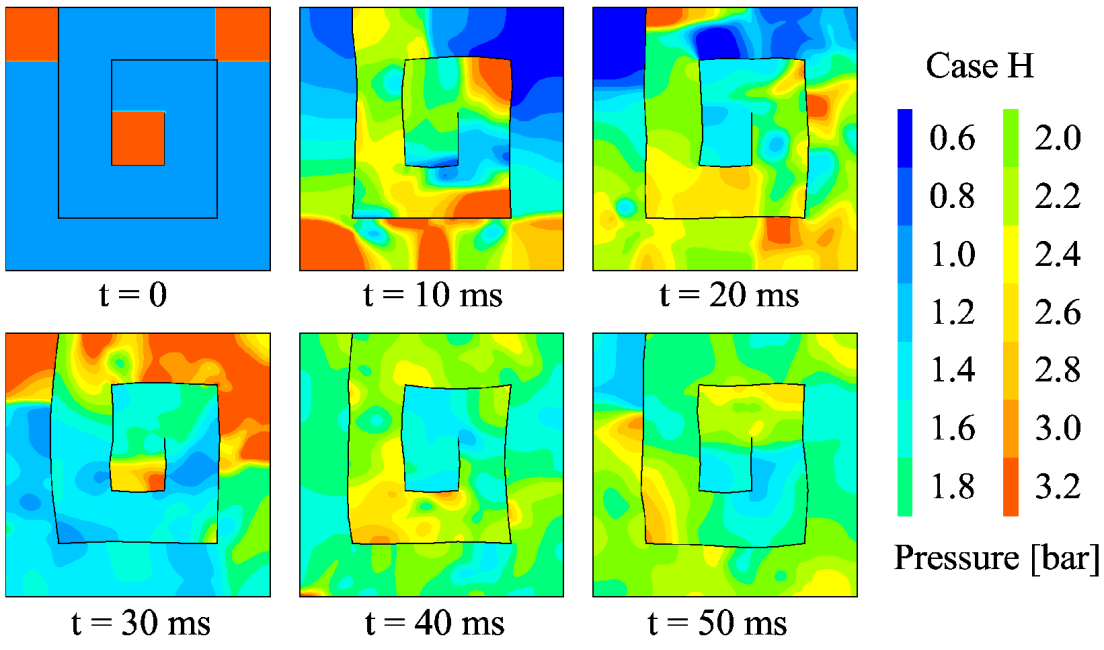
Labyrinth: fluid pressures in case E (reference solution)



Labyrinth: displacement δ_1 in cases E (reference) to H (nonconforming mesh solutions)

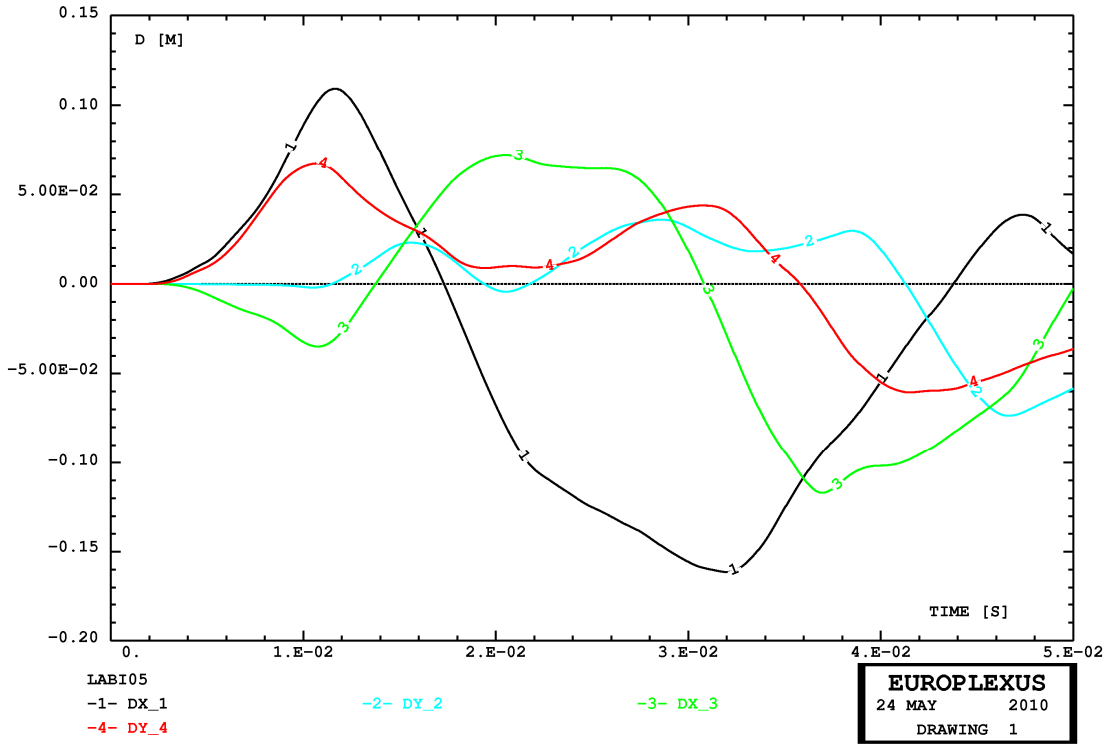


Labyrinth: fluid pressures at 10 ms in all test cases

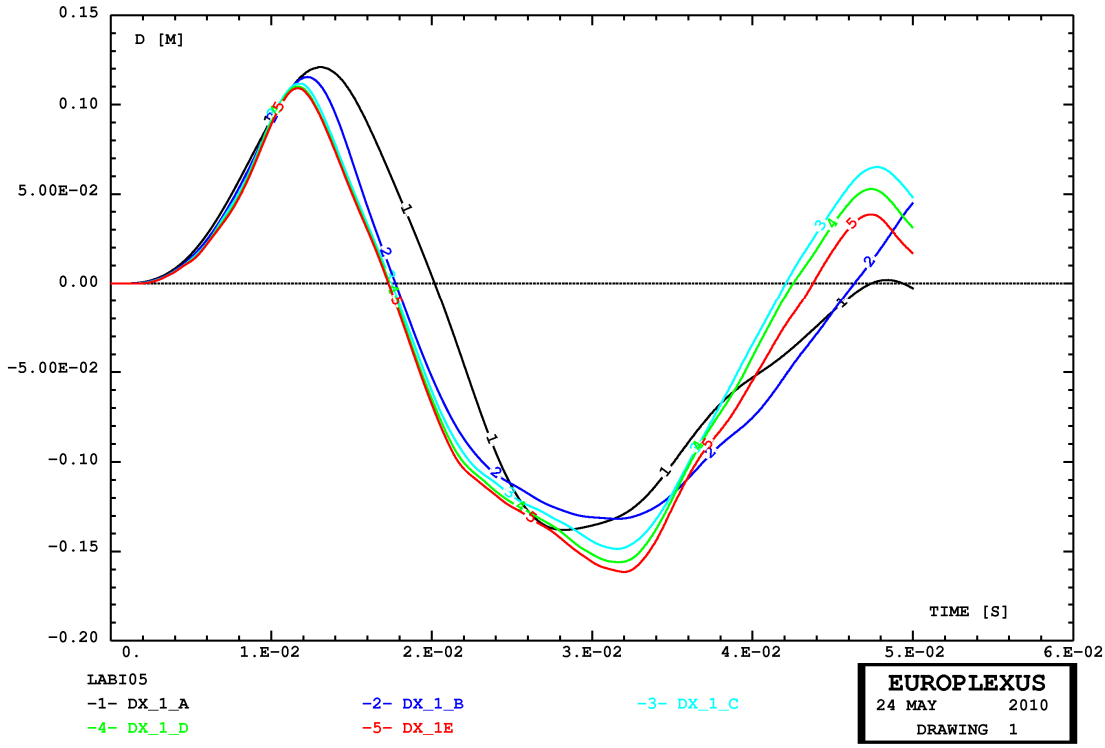


Labyrinth: fluid pressures in case H

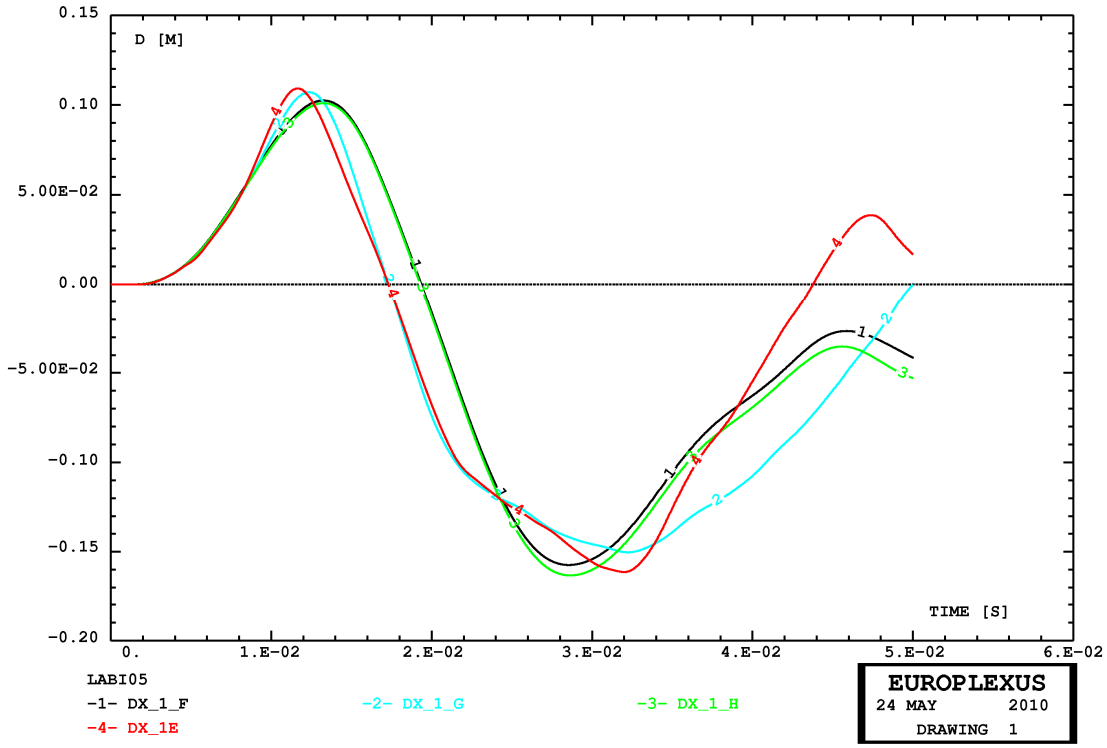
Displacements in the reference solution (case E).



Displacement 1 in solutions A to E:



Displacement 1 in solutions E (reference), F, G and H.



Comparison of solutions without and with partitioning