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again the general patterns and magnitudes are similar to those in case 7.1.

The use of 4000 steps to equilibrate displacements/stresses between thermal steps improved the displacement modelling, reducing the unbalanced force considerably.

Plots of joint normal displacement/stresses and shear displacement/stresses were more irregular for Case 7.3 and very dependent on the tolerance specified. In re-examining Case 7.1, the plots 7fjnd.emf, 7fjns.emf, 7fjsd.emf and 7fjss.emf are all clipped due to a zero tolerance variable value. Other tolerances produce plots of different character.

Plots of normal and shear displacement at the center of the main joint show very small normal and shear displacements in both Case 7.1 and 7.3. The patterns of displacement differ somewhat, likely as a result of the increased number of mechanical steps used in Case 7.3.

There was no joint slip in either of these two cases, consistent with the fictitiously high strength values used for the joint.

Case 7.4 (Inclined transgressing joint, slip allowed)

This UDEC case was run using input from file INCLINED2.TXT. The input file is shown on page 87. This file modifies the joint properties as per case 7.2 and creates a similar suite of plots with some additions (PLINE plots of shear stress, normal stress and displacement along the joint trace). Results are plotted on the pages following the input file.

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```
; Case 7.4 Inclined transgressing joint in a heated
; infinite rock mass (slip allowed on joint)
;
config thermal
set mech on
;
; Geometry
;
rou 0.001
bl 0,0 0,100 100,100 100,0
crack 0 25 100 75 ; Main joint
crack 0 22.2049 100 72.2049 ; Top
crack 0 16.6147 100 66.6147 ; Bottom
crack 48.8819 46.6459 51.1180 42.1738 ; Left side
crack 53.3541 48.8820 55.5902 44.4098 ; Right side
;
;
gen quad 2.0
;
; Material properties
;
prop m=1 de=2210.0 k=19.0e9 g=13.0e9
prop jm=1 jkn=19.0e11 jks=13.0e11
prop jm=1 jcoh=1.0e20 jfric=0.0 jten=1.0e20 jd=0
prop m=1 thexp=15.0e-6 cond=20.0 spec=1000.0
prop jm=2 jkn=19.0e11 jks=13.0e11
prop jm=2 jcoh=100.0e3 jfric=20.0 jten=1.0e6 jd=0
change jmat=2 range block 358 143
change jmat=2 range block 143 358
;
; Initial conditions
;
initem 34.0 0 100 0 100
;
; Boundary conditions
;
bound yvel 0.0 range (0,100) (-0.1, 0.1)
bound yvel 0.0 range (0,100) (99.1, 100.1)
bound xvel 0.0 range (-0.1, 0.1) (0,100)
bound xvel 0.0 range (99.1, 100.1) (0,100)
;
; Apply heat source
;
thapp source 50000 0 range 51.1180 53.3541 44.4098 46.6459
;
; Thermal histories
;
thist temp 52.236, 45.528 ; 1
thist temp 51.342, 47.317 ; 2
thist temp 50,50 ;3
thist temp 45.528, 58.944 ; 4
thist temp 38.819, 72.361 ; 5
thist temp 27.639, 94.721 ; 6
;
; Mechanical histories
;
hist ydisp 52.236, 45.528 ; 1
hist ydisp 51.342, 47.317 ; 2
hist ydisp 50,50 ;3
hist ydisp 45.528, 58.944 ; 4
hist ydisp 38.819, 72.361 ; 5
hist ydisp 27.639, 94.721 ; 6
hist unbalanced ;7
hist ndis 50 50 ;8
hist sdis 50 50 ;9
;
; Plot lines
;
set pline 0 26 100 76 100 ; 1
set pline 0 25 100 75 100 ; 2
set pline 0 24 100 74 100 ; 3
;
; Thermal mechanical analysis
;
;
set nther 2500
set nmech 2500
damp auto
run age 1000000 temp 50
step 2500
;
save 7i2final.sav
;
set plot emf color
title
Case 7.4  Thermally-Induced Joint Displacement (Inclined, Slip Allowed)
;
; Geometry
;
set out 7i2grid.emf
set color iw
plo zone green blo iw
copy

; Joint condition plots
;
set out 7i2jndl.emf
set color iw
plot joint 0 25 100 75 ndisp 5
copy
;
set out 7i2jnsl.emf
set color iw
plot joint 0 25 100 75 nstr 5
copy
;
set out 7i2jsdl.emf
set color iw
plot joint 0 25 100 75 sdisp 5
copy
;
set out 7i2jssl.emf
set color iw
plot joint 0 25 100 75 sstr 5
copy
;
set out 7i2shear.emf
set color iw
plo blo iw shear red
copy
;
set out 7i2slip.emf
set color iw
plo blo iw slip red
copy
;
; Contour plots
;
set out 7i2tempc.emf
set color iw
plot temp fill int 50 temp int 50 iw blo iw
copy
;
set out 7i2dispc.emf
set color iw
plot disp green blo iw
copy
;
set out 7i2xdc.emf
set color iw
plot xd fill xd iw blo iw
copy
;
set out 7i2ydc.emf
set color iw
plot yd fill yd iw blo iw
copy
;
set out 7i2sig1c.emf
set color iw
plot sig1 int 1e7 fill sig1 int 1e7 iw blo iw
copy
;
set out 7i2sig2c.emf
set color iw
plot sig2 int 1e7 fill sig2 int 1e7 iw blo iw
copy
;
set out 7i2sdifc.emf
set color iw
plot sdiff int 1e7 fill sdiff int 1e7 iw blo iw
copy
;
set out 7i2sevol.emf
set color iw
plot evol fill evol iw blo iw
copy
;
; History plots
;
set out 7i2thisth.emf
set color iw
plo thist 1 2 3 4 5 6
copy
;
set out 7i2ydhisth.emf
set color iw
plo hist 1 2 3 4 5 6
copy
;
set out 7i2unbalh.emf
set color iw
plo hist 7
copy
;
set out 7i2jnsh.emf
set color iw
plo hist 8 9
copy
;
; Plot lines
;
set out 7i2pl1ss.emf
set color iw
plo pline 1 ss
copy
;
set out 7i2pl1ns.emf
set color iw
plo pline 1 nstr
copy
;
set out 7i2pl1d.emf
set color iw
plo pline 1 disp
copy
;
set out 7i2pl2ss.emf
set color iw
plo pline 2 ss
copy
;
set out 7i2pl2ns.emf
set color iw
plo pline 2 nstr
copy
;
set out 7i2pl2d.emf
set color iw
plo pline 2 disp
copy
;
set out 7i2pl3ss.emf
set color iw
plo pline 3 ss
copy
;
set out 7i2pl3ns.emf
set color iw
plo pline 3 ns
copy
;
set out 7i2pl3d.emf
set color iw
plo pline 3 disp
copy
;
ret
```

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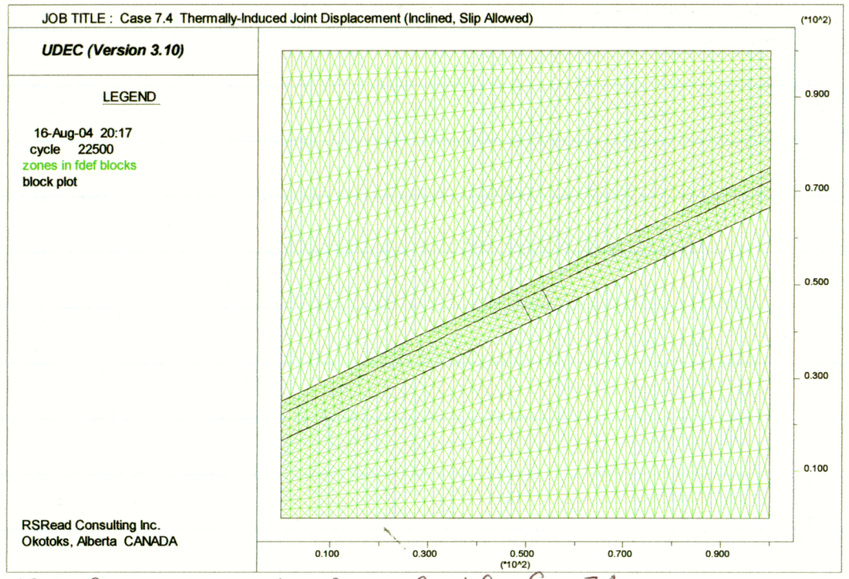
UDEC input file INCLINED2.TXT for case 7.4.



From file 7i2grid.emf Grid for Case 7.4.

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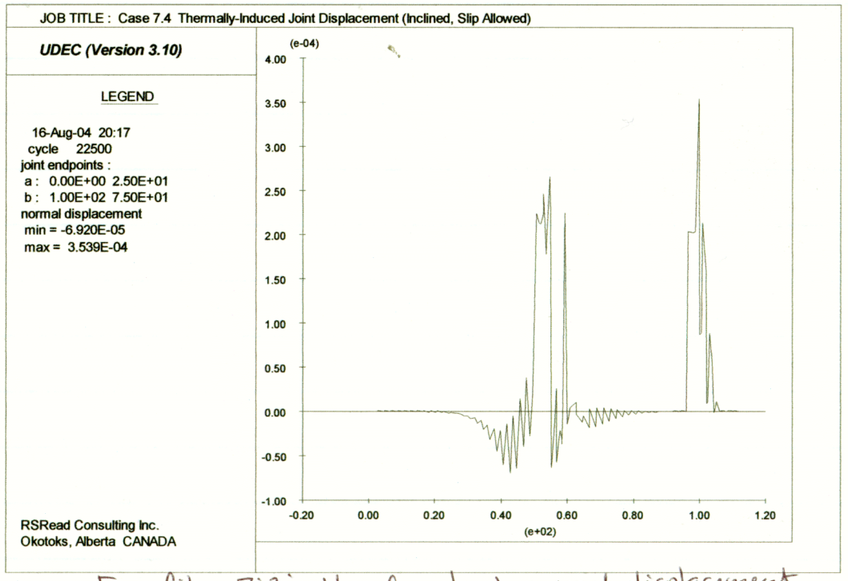
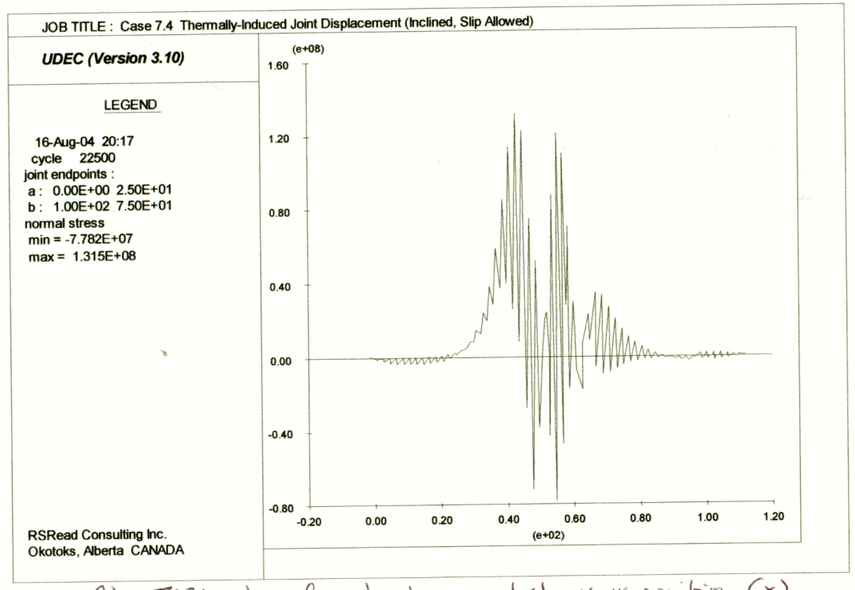


From file 7i2jndl.emf Joint normal displacement vs position (x)



From file 7i2jnsl.emf Joint normal stress vs position (x)

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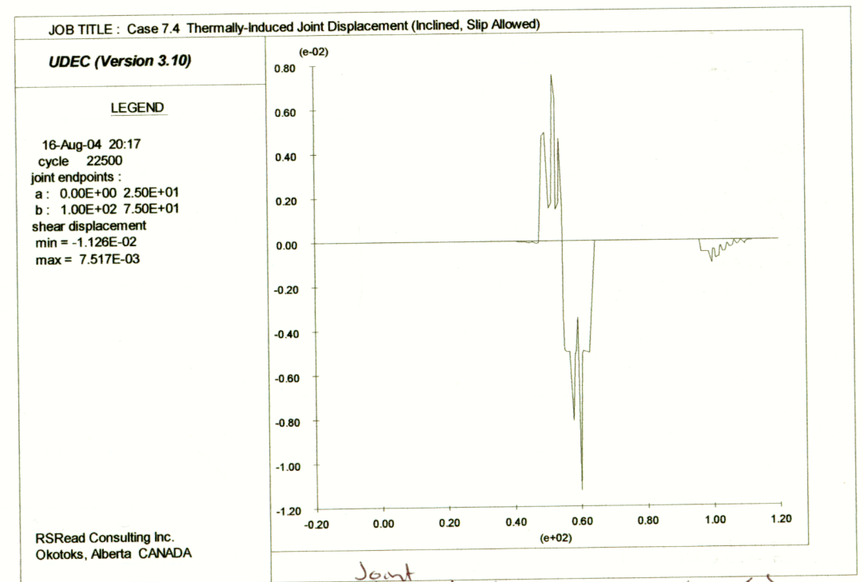

From file 7i2jsdl.emf Joint shear displacement vs position (x)

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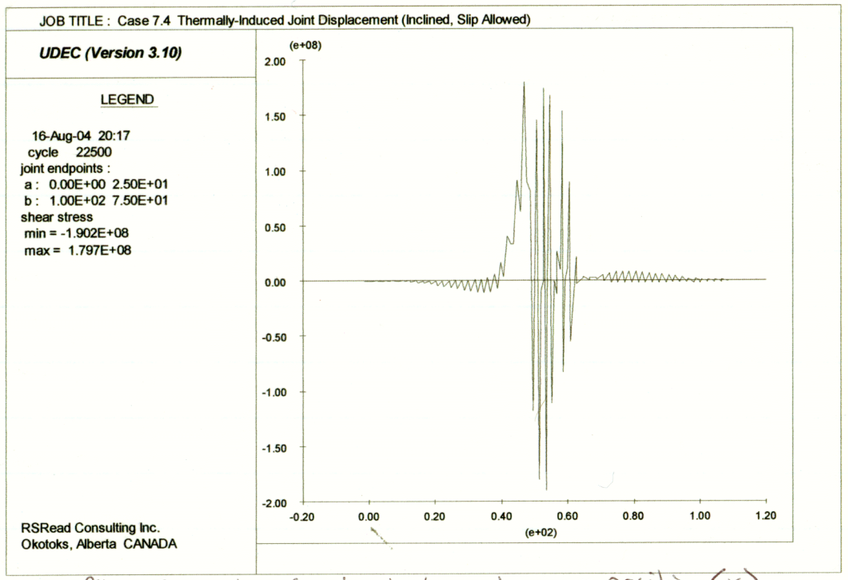

From file 7i2jss1.emf Joint shear stress vs position (x)

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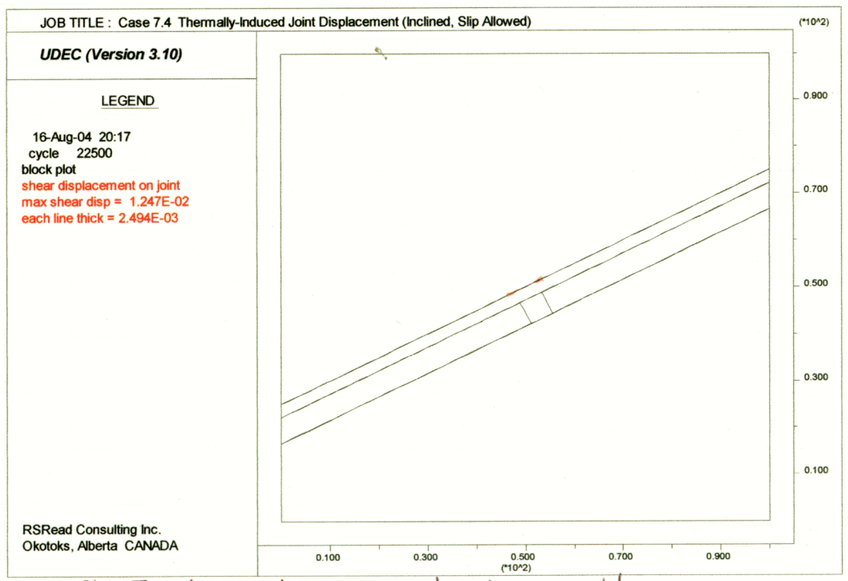

From file 7i2shear Joint shear displacement

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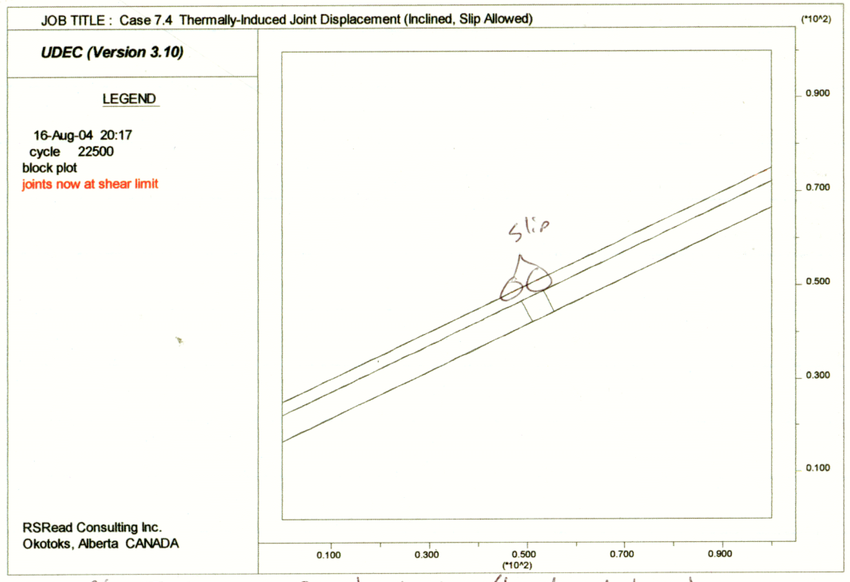

From file 7i2slip.emf Joint slip (localized slip above heated zone).

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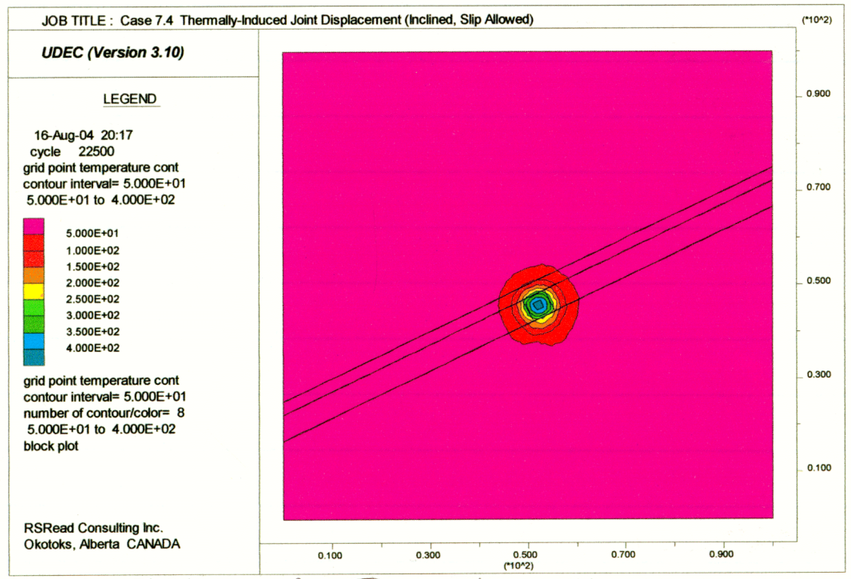

From file 7i2temp.enf Temperature contours.

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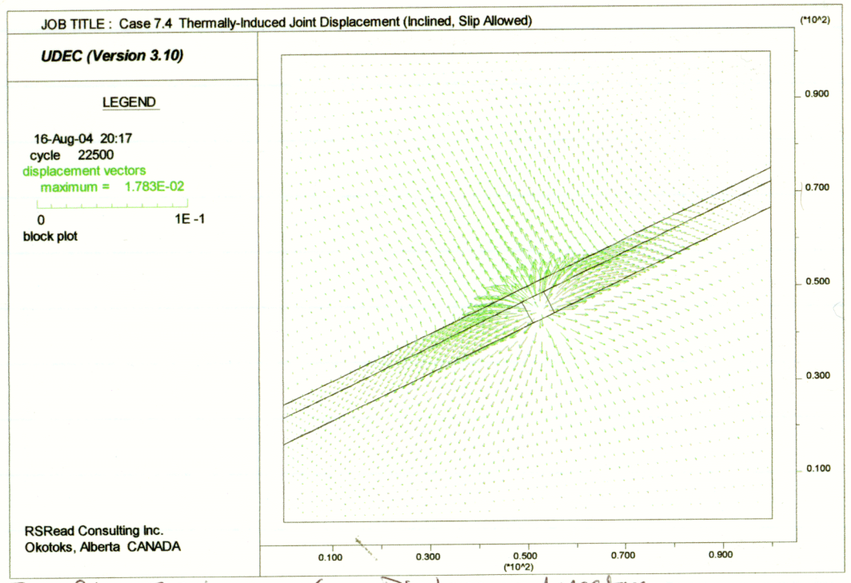

From file Ti2dispc.emf Displacement vectors.

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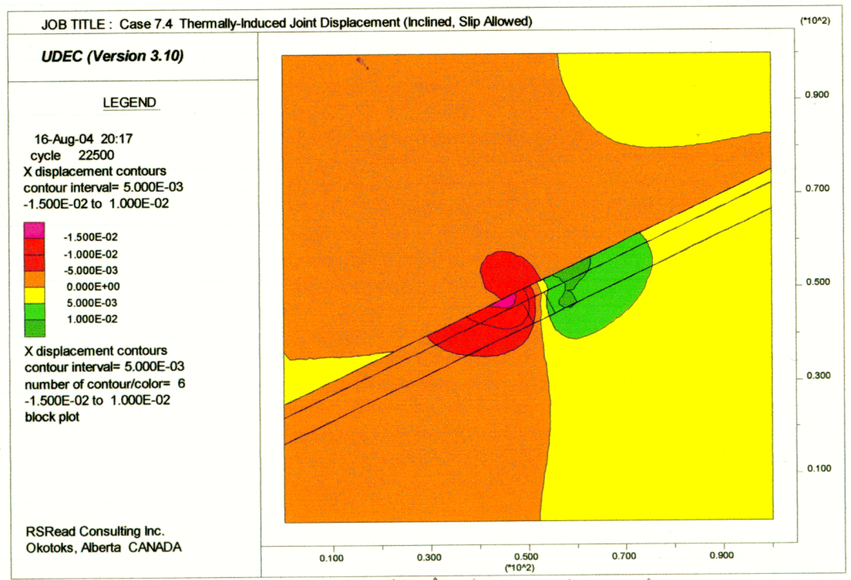

From file Ti2xdc.emf X-displacement Contours

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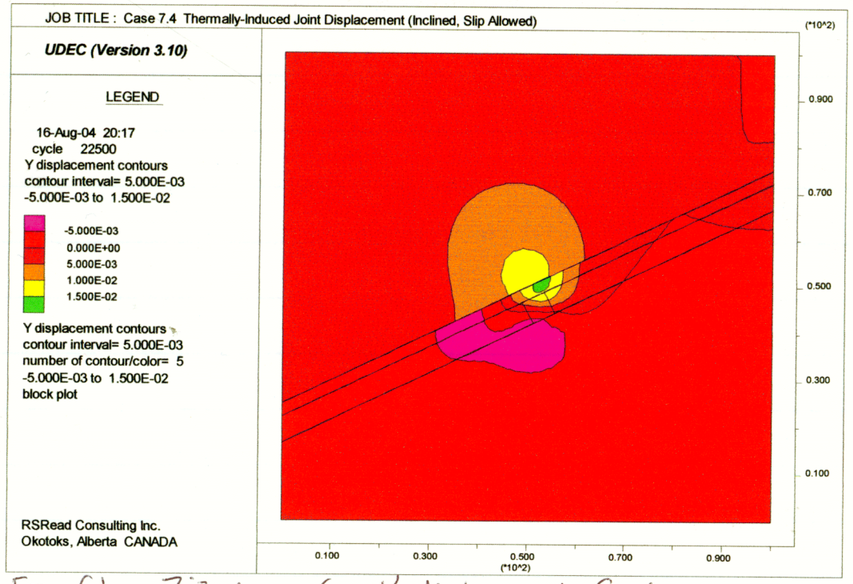
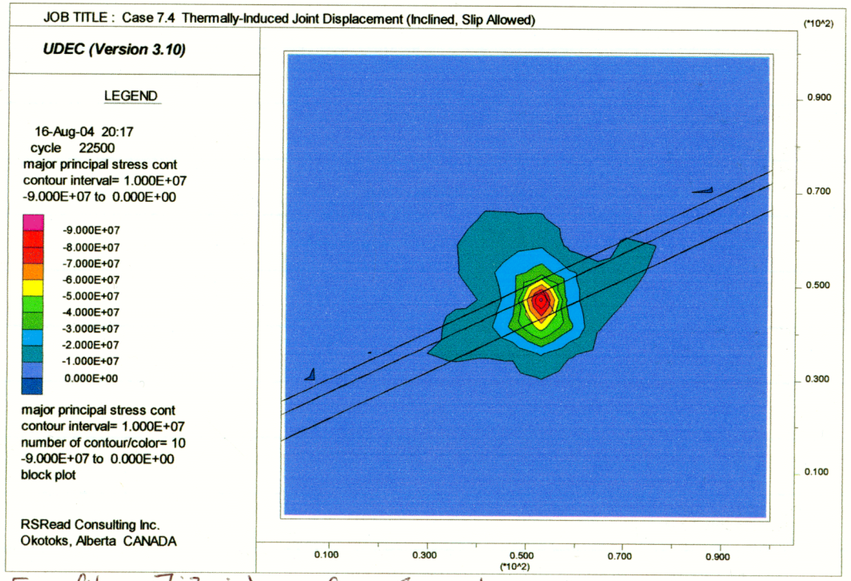


From file Ti2ydc.emf Y-displacement Contours.

Aug 6/04



From file Ti2sig1c.emf Sigma 1 contours.

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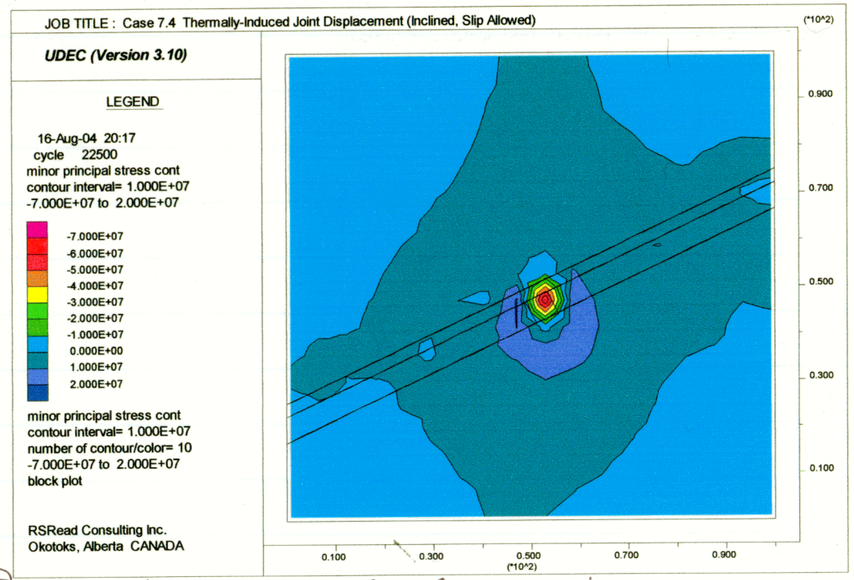

From file Ti2sig2c.emf Sigma 2 contours.

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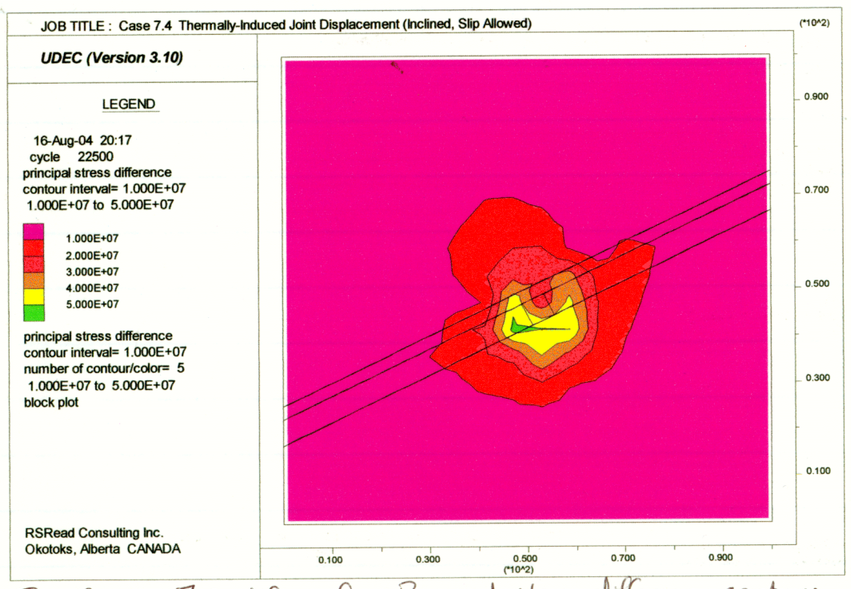

From file Ti2sdifc.emf Principal stress difference contours

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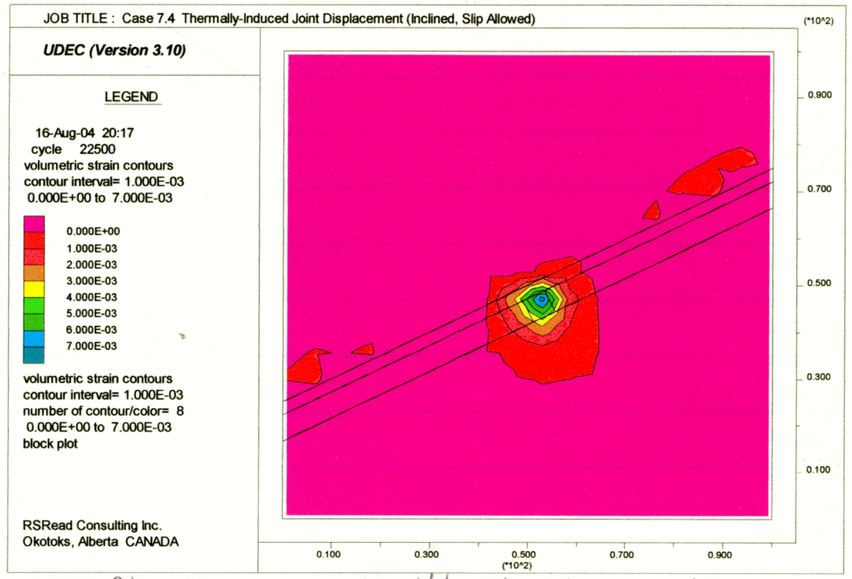

From file Ti2sevol.emf Volumetric strain contours.

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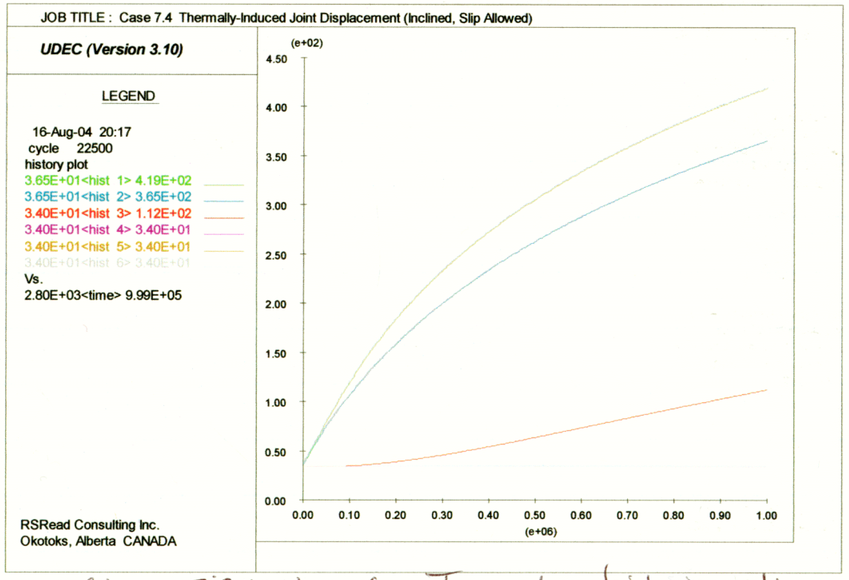
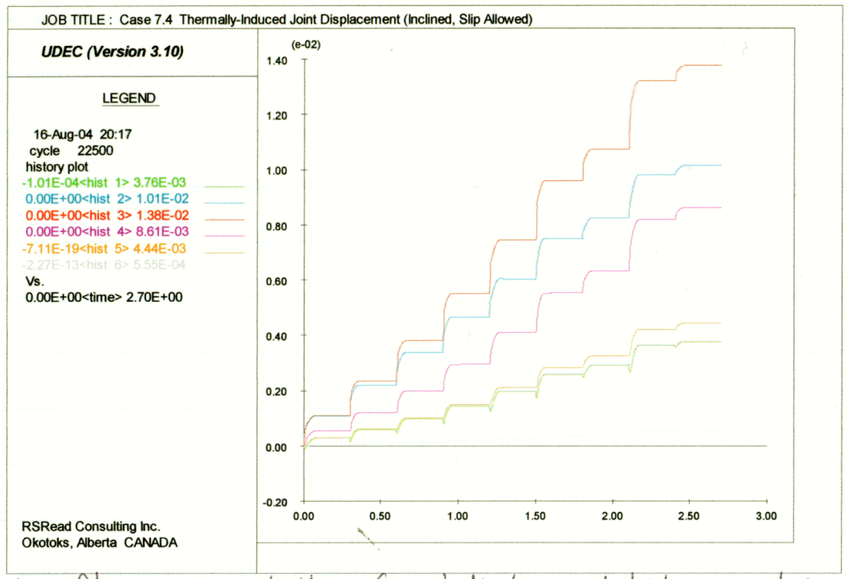
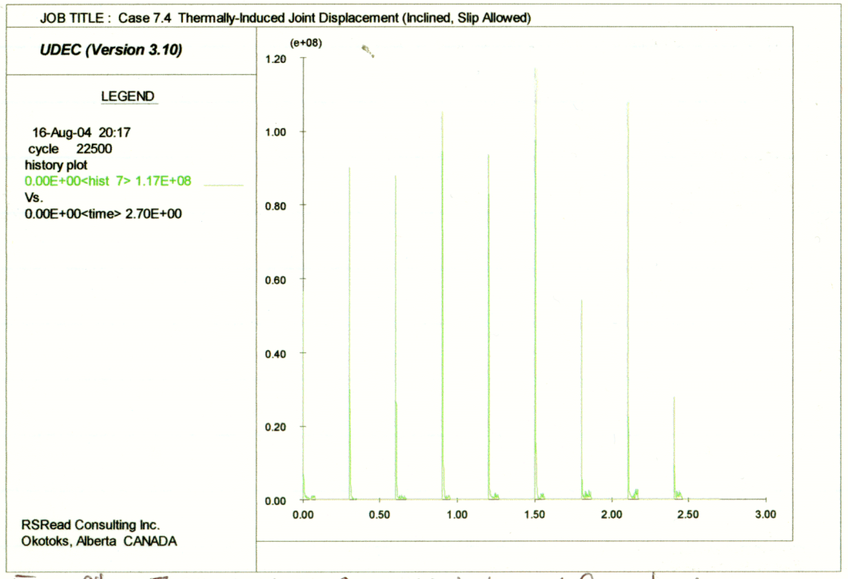


From file Ti2thisth.emf Temperature histories vs time.

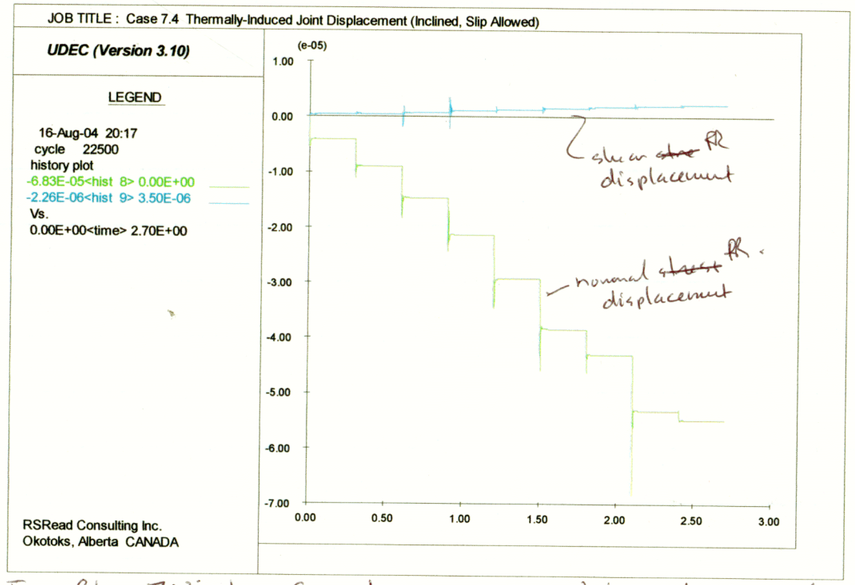


From file 7i2ydhisth.enf Y-displacement history vs step.

Aus 16/04

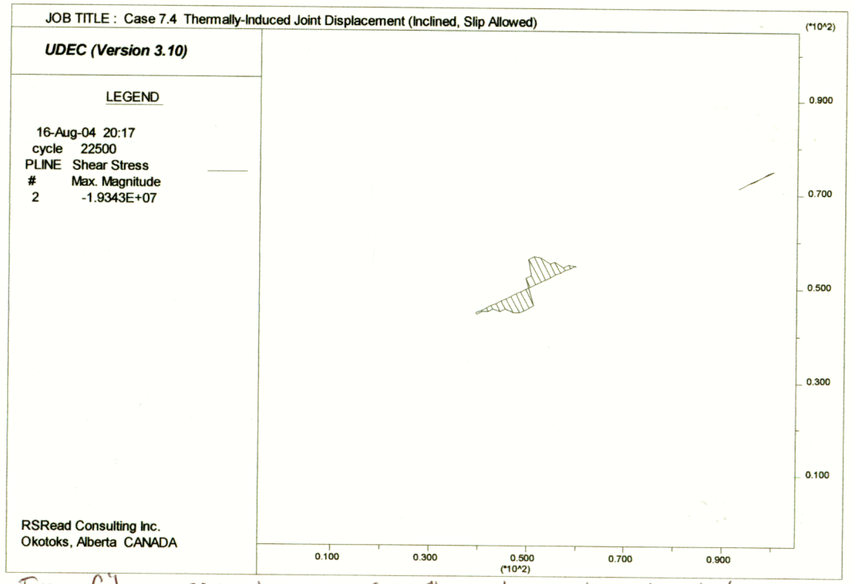


From file 7i2unbalh.enf Unbalanced force history.

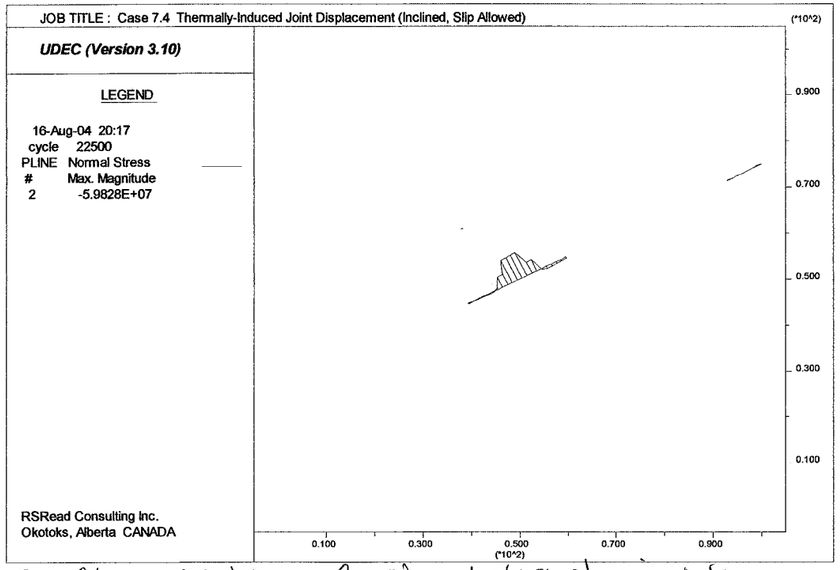


From file 7i2jnsh.enf Joint normal and shear displacement at x=50 y=50

Aus 16/04



From file 7i2plzss.enf Shear stress along joint trace.



From file 7i2pl2ns.emf Normal stress along joint trace.

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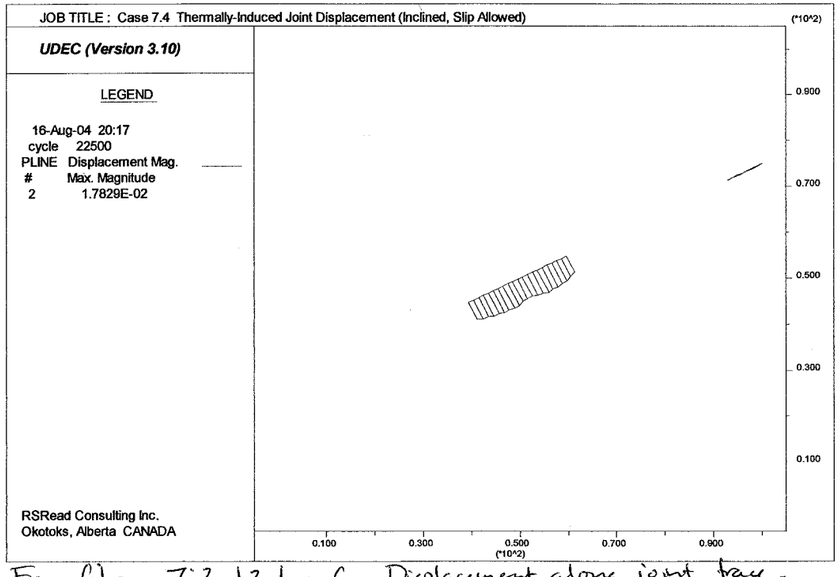

From file 7i2pl2d.emf Displacement along joint trace.

Results (Case 7.4)

As in Case 7.2, the introduction of realistic joint properties results in shearing along the joint above the heated zone. The maximum normal stress (compression) occurs at x = 50, y = 50 the center of the joint. The maximum shear displacement occurs ~~on~~ above the flanks of the heated zone, and is on the order of 1.25×10^{-2} m (ie 12.5 mm). This compares with 13.6 mm shear displacement in Case 7.2. The maximum total displacement in case 7.2 was 16.8 mm; the total displacement reached a maximum of 17.8 mm in Case 7.4. These minor differences are likely due to the difference in grid geometry and the fact that more mechanical timesteps were used in case 7.4 to reach equilibrium. As in case 7.2, there is a major disruption in the stress distributions caused by displacement (slip) on the joint.

The temperature distributions in these two cases are very similar, with only slight differences in contouring caused by the differences in the grid geometry. Both cases experienced unbalanced forces on the order of $1e^8$ due to the large temperature interval chosen (50°C). In combination with zero initial stress, the thermal-mechanical stresses generated by heating were sufficiently high to initiate slip.

To determine the general pattern and timing of slippage along the joint, a modification was made to the UDEC input file INCLINED2.TXT to plot histories of normal displacement, shear displacement and strength/stress

ratios at points along the joint at the following coordinates

x = 0 y = 25	x = 60 y = 55
x = 10 y = 30	x = 70 y = 60
x = 20 y = 35	x = 80 y = 65
x = 30 y = 40	x = 90 y = 70
x = 40 y = 45	x = 100 y = 75.
x = 50 y = 50	

```
;
; Histories of normal displacement along joint
;
hist ndis 0 25 ;8
hist ndis 10 30 ;9
hist ndis 20 35 ;10
hist ndis 30 40 ;11
hist ndis 40 45 ;12
hist ndis 50 50 ;13
hist ndis 60 55 ;14
hist ndis 70 60 ;15
hist ndis 80 65 ;16
hist ndis 90 70 ;17
hist ndis 100 75 ;18
;
; Histories of shear displacement along joint
;
hist sdis 0 25 ;19
hist sdis 10 30 ;20
hist sdis 20 35 ;21
hist sdis 30 40 ;22
hist sdis 40 45 ;23
hist sdis 50 50 ;24
hist sdis 60 55 ;25
hist sdis 70 60 ;26
hist sdis 80 65 ;27
hist sdis 90 70 ;28
hist sdis 100 75 ;29
;
; Histories of sratio along joint
;
hist srat 0 25 ;30
```

Modified plot commands for INCLINED2.TXT to produce temporal and spatial histories.

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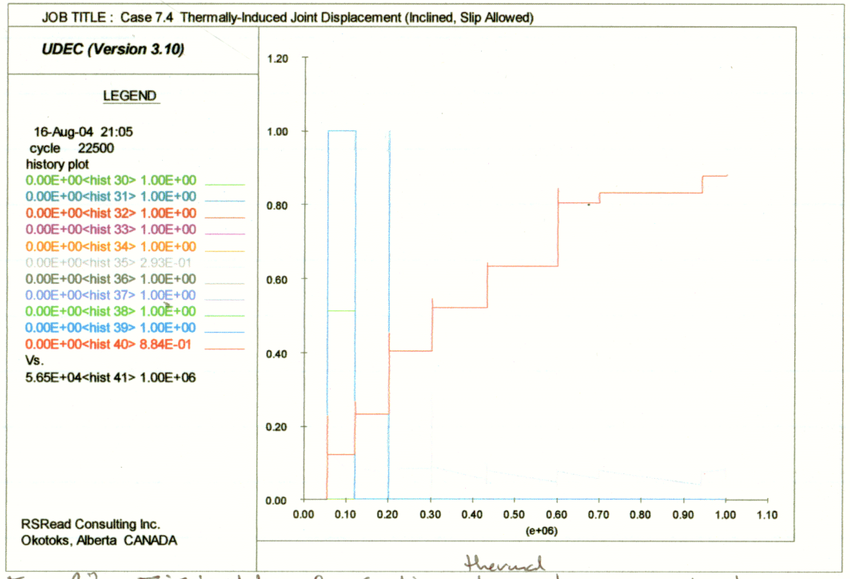
```
hist srat 10 30 ;31
hist srat 20 35 ;32
hist srat 30 40 ;33
hist srat 40 45 ;34
hist srat 50 50 ;35
hist srat 60 55 ;36
hist srat 70 60 ;37
hist srat 80 65 ;38
hist srat 90 70 ;39
hist srat 100 75 ;40
;
hist thtime ; 41
```

The plots generated using these commands are shown on the next few pages. These plots are quite crowded - modified versions would be preferred for future runs. These plots show that the majority of shear and normal displacement occurs on the first calculation cycle near the heat source, then progresses along the joint with further heating.



From file Tiljsrht.enf Sratio vs. time showing early slippage on joint.

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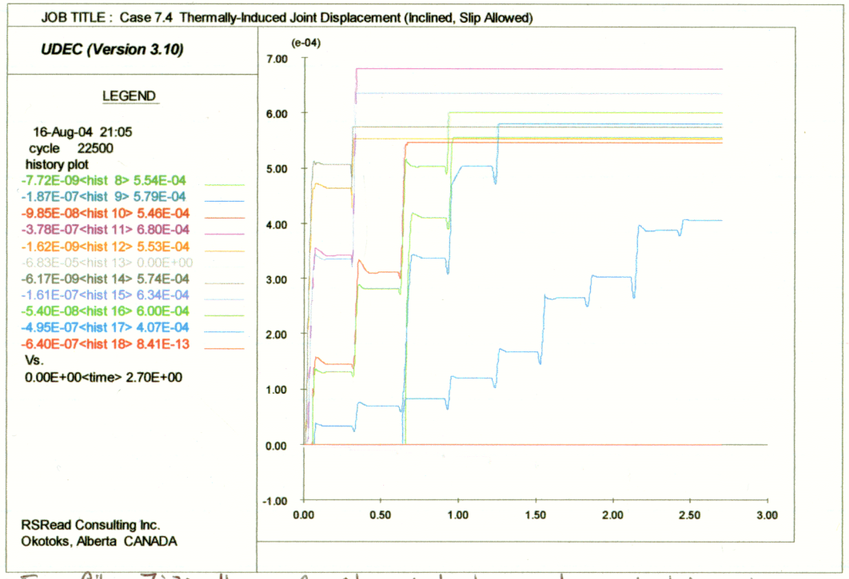
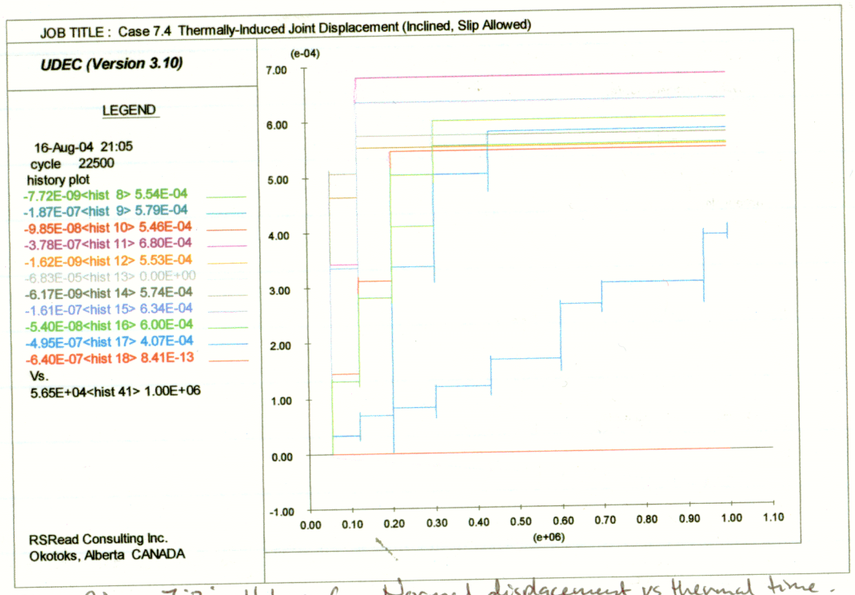


From file Tiljnths.enf Normal displacement vs calculation time - Most displacement occurs at early time -



From file 7i2jsndht.emf Normal displacement vs thermal time.

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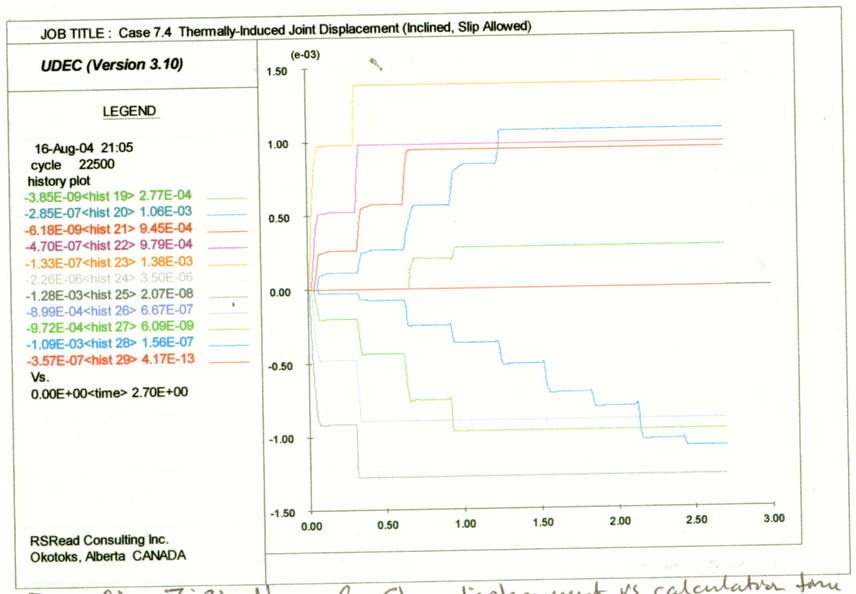
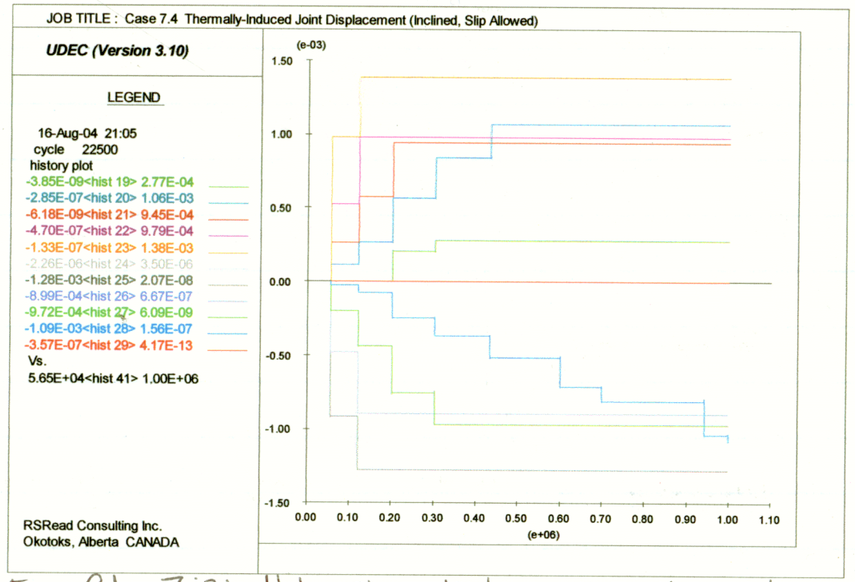


From file 7i2jsdhs.emf Shear displacement vs calculation time (Most shear displacement occurs on the first calculation cycle).



From file 7i2jsdht Shear displacement vs thermal time.

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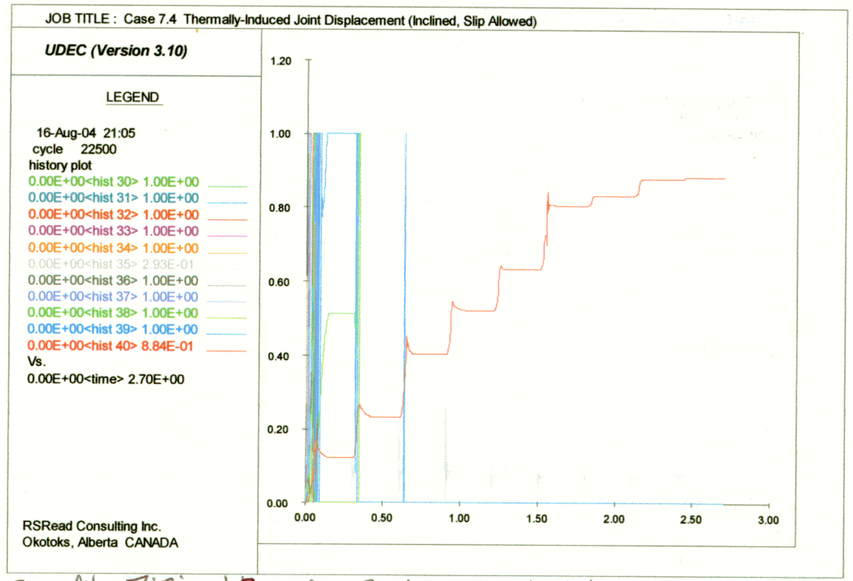

From file 7i2jsrhs.emf Sratio vs calculation time.

R.

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Summary of Cases 7.1 - 7.4 (UDEC)

These four cases provide a basis for comparison with FLAC 4.0. Several additional cases could be run with each code to check behavior under stress conditions typical of a repository at depth. Additional cases should use property values from other numerical studies of Yucca Mountain. (eg. Hydrological Implications of Thermally Induced Geomechanical Response at Yucca Mountain, Nevada - Ofoegbu CNWRA). Another source of information is a 1999 paper by Rui Chen (Analyses of drift stability and rockfall due to earthquake ground motion at Yucca Mountain, Nevada. - Proc. 37th US rock Mech. Symp. Vol. 2, pg 759 - 766). The Drift Degradation Analysis is another source of information. (ANL-MGR-EBS-MD-000027, Rev2)

The main plots that are of use in this analysis are

1) Grid (ZONES BLO)
2) Shear displacement (SHEAR) → max shear displacement.
3) Temperature (TEMP) → contours plus histories.
4) Slip on joint (SLIP) → multiple plots to show progression.
5) Displacement (DISP) → max displacement.
6) Unbalanced force (HIST UNBAL) → check on process
7) Normal displacement (HIST NDIS) → points on joint
8) Shear displacement (HIST SDIS) → points a joint
9) SRATIO (HIST SRATIO) → points on joint
10) Thermal time (HIST THT) → to plot on x axis.

Plots of stresses are good visual checks but tend to be more qualitative in nature.

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Properties for Future Runs.	Chen 1999	Ofoegbu *	Drift Deg. **	UDEC & FLAC selected Values
Property or Boundary/Initial Condition				
Young's modulus (MPa)	$32e^3$	$7.8e^3$ - $32.6e^3$	$33.03e^3$	$33e^3$
Poisson's ratio	0.21	0.21	0.21	0.21
Rock friction angle (°)	20°	27.5 - 34.4	42	42
Rock cohesion (MPa)	43	2.82 - 5.08	47.2	47.2
Rock tensile strength (MPa)	5		11.56	11.56
Rock Unconfined Compressive Strength (MPa)	166		167.9 Non Tptpmn hydrostat	168 m=23.75 s=1.0 a=0.5 HB
Rock Density (kg/m³)	2297	2210	2148 - 2310	2210 ~~2229~~ RR Aug 16/04
Fracture Friction Angle (°)	38		41	41°
Fracture Cohesion (MPa)	0.08		0.1	0.1
Fracture Tensile Strength (MPa)	0.04			0.04
Fracture Normal and Shear Stiffness (MPa/m)	$1.^{\circ} \times 10^{+5}$		$5.^{\circ}e^4$	$5e^4$
Ini. Temperature (°C) (Repository horizon)		18.7°C surface 34.3°C 670m depth		25
~~Fracture Friction Angle~~ RR Aug 16/04				
Thermal Expansion Coefficient (K^{-1})	6×10^{-6}	$7.14 - 15.5e^{-6}$	$7.09 - 10.34^{\circ}e^{-6}$	$10e^{-6}$
Thermal Conductivity (W/m-k)	2.1	2.13	1.49 - 2.13 ~~1.64 - 1.89~~ RR Aug 16/04	2.13
Specific Heat (J/Kg-k)	932	969, 1741, 988	908 - 990 ~~811 - 954~~ RR Aug 16/04	990
Initial vertical stress gradient (MPa/m)	~~0.027~~ RR Aug 16/04	0.022		0.022 σ_1 = 7 MPa (rep)
Initial horizontal-to-vertical stress ratio	~~0.266~~ RR Aug 16/04	0.266		0.266 σ_2 = 1.9 MPa (rep)
Initial Thermal loading (kW/m²)	~~1.226~~ RR Aug 16/04	1.226	1.45	1.45
~~Density~~ RR Aug 16/04. Repository Depth (m)		320	281	320
Bulk modulus (GPa)			19.2	19.2
Shear modulus (GPa)			13.6	13.6
Joint Dilation (°)			0 15	0, 15
Joint orientation (Az°/Dip°)			122/84 *** 195/85 *** 306/09 *** ~~Tptpmn~~ RR Aug 16/04.	~~265° inclined~~ RR Aug 16/04 14° inclined.

* Ofoegbu - Hydrological Implications of Thermally Induced Geomechanical Response at Yucca Mountain, Nevada.

** Drift Deg. - ANL-EBS-MD-000027 Rev 02 (June 2003)

*** 120/84, 215/88, 329/14 } from FRACMAN for Tptpmn