Comparison of EFG and Standard Elements for Thermal-mechanical Metal-forming Simulations

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Abstract:

LS-DYNA 970.5424 simulations of metal-forming with thermal effects due to plastic heating are presented. Standard and element free Galerkin (EFG) elements are used. The results are compared to implicit solutions where possible. The EFG simulation demands higher computation time and shows a slightly softer behaviour. The EFG method does not introduce non-physical energy in the system to control hourglass modes and shows the potential for more accurate calculations in the future.

Keywords:

Coupled Simulation, EFG, Implicit, Adaptive

1 Introduction

In metal-forming processes such as rolling, extrusion and stamping, large plastic deformation as well as large temperature changes may occur. The temperature changes of the body are either due to external heating, or to the conversion of mechanical work into heat through plastic deformation or friction. Since the material properties and plasticity parameters are dependent on temperature, temperature changes have a significant influence on the deformation process; e.g. temperature increase due to plastic heating causes material softening. At the same time a non-homogeneous temperature distribution can, after cooling, lead to undesirable residual stress or deformation. A coupled thermal-mechanical numerical analysis is necessary to simulate the physical phenomena observed. This can be done with LS-DYNA 970.5434 as in this paper.

Shapiro [1,2] treated a benchmark problem of Lugt and Hueting [3]. This paper goes beyond Shapiro's as it compares standard solid element formulation and the novel EFG (element free Galerkin) method in LS-DYNA [4]. EFG does not introduce non-physical energy in system to control hourglass modes, and promises more robustness and smoother results for the cost of longer computation times. An objective is to show that the EFG elements allow for thermal-mechanical coupling in LS-DYNA.

2 Method

In [5] a 2D-Version of the problem of Lugt and Hueting can be found. A low carbon steel sample has an initial height of 36mm, radius of 9mm, and initial temperature of 20C. The total axial compression between two perfectly rough cylinders is 44% in 1.6s. There is no heat transfer to the environment.

In [5] and here `*MAT_PIECEWISE_LINEAR_PLASTICITY` is used to model the material. It accounts for the heating by plastic deformation. This material does not incorporate thermal expansion as `*MAT_ELASTIC_PLASTIC_THERMAL` or `*MAT_ELASTIC_VISCOPLASTIC_THERMAL`. The latter supports input of a true stress strain curve, which is scaled by a factor for different temperatures. Shapiro [2] derived an approximation for the data of Lugt and Hueting [3]. EFG is possible with this material, too. With `*MAT_THERMAL_ISOTROPIC` the thermal properties, which are linear and do not depend on temperature, are modelled. There is no feedback of the thermal field into the mechanical field for `*MAT_PIECEWISE_LINEAR_PLASTICITY`.

In this paper I treat an eighth cylinder with solid elements, because no EFG shells are available in LS-DYNA at the moment. An implicit EFG solid formulation is not available at the moment, too. Therefore, only a comparison to implicit calculations with standard element formulation was done. Introductory simulations [6] were performed to establish the mesh density shown in figure 1 taking into account the accuracy of the stress state prediction at the center of the sample, which is the lower left corner, and the computational efficiency. This mesh consisted of 432 elements and 610 nodes. The calculations were carried out on a 2.8 GHz Intel CPU with 1 GB 266 DDR memory. It is advisable to run a SSE optimized executable in this case, which is about 20% faster. In the beginning of August 2004 the first 5424 version runs slower than 3858! However, the EFG implementation has developed.

LS-DYNA treats the EFG solid (`ELFORM`=41) pretty much as just another element formulation for a solid. Inserting a `*SECTION_SOLID_EFG` card and switching the `SECID` parameter on the `*PART` card starts an explicit EFG calculation, as shown in the abstracted input deck in the appendix. It is only necessary to add two cards for an implicit solution. Note, however, that LS-DYNA does not tolerate the implicit cards in the input deck along with EFG cards, even if `IMFLAG` on `*CONTROL_IMPLICIT_GENERAL` is not set.

LS-DYNA computes the solution with a thermal and a structural time-stepping process that work independently. The thermal time stepping is always implicit. Full backward Euler method (`TIP`=1 on `*CONTROL_THERMAL_TIMESTEP`) is the appropriate choice. The structural time stepping works either implicit or explicit. The rate of mechanical motion, mechanical deformation, and rate of heat transfer must all be considered in selecting an appropriate time step.

In this quasistatic simulation, in which the inertia effects are insignificant [7], the explicit time step is fixed to 0.1ms by mass scaling (`DT2MS` on `*CONTROL_TIMESTEP`). This means about 2000 cycles per mm motion of the compressing rough cylinder. By switching to a pure mechanical analysis and reducing the time step one can proof that the deformation history does not change. For an implicit solution mass scaling is not necessary.

During the investigation I learned that LS-DYNA does not account for the plastic heating perfectly. This can be seen if mechanical and thermal step are set equal to 0.1ms. The peak temperature for this simulation differs considerably (91.6C to 129.7C) to that with doubled thermal time step. Then the peak temperature stays nearly constant for a thermal time step up to 10ms (128.7C). I recommend, therefore, about one thermal time step for each 10 structural explicit time steps. An adaptive scheme with minimum and starting time step of 0.1ms and a maximum time step of 10ms yields 129.1C. A proper accumulation of the plastic heating between thermal time steps remains a desirable development in LS-DYNA.

If an implicit structural time stepping is chosen, minimum and maximum time step should be the same as for thermal time stepping. So the count of thermal and implicit structural time steps is of the same order. In this case here an aggressively high maximum time step (`DTMIN` on `*CONTROL_IMPLICT_AUTO`) of 0.1s would yield a convergent implicit solution with a peak temperature that is factor three smaller in spite that the peak plastic strain only diminishes by about 5%.

To gain a reference solution explicit and implicit 2D simulations with fine mesh adaptivity were done [6]. The influence of the various modelling options showed that even for a fine mesh there is a scatter of about 1%. So this becomes the criterion for a significant difference. Axisymmetric EFG simulations are not possible by now. The axisymmetric element ELFORM=15 needs hourglass control, EFG would not.

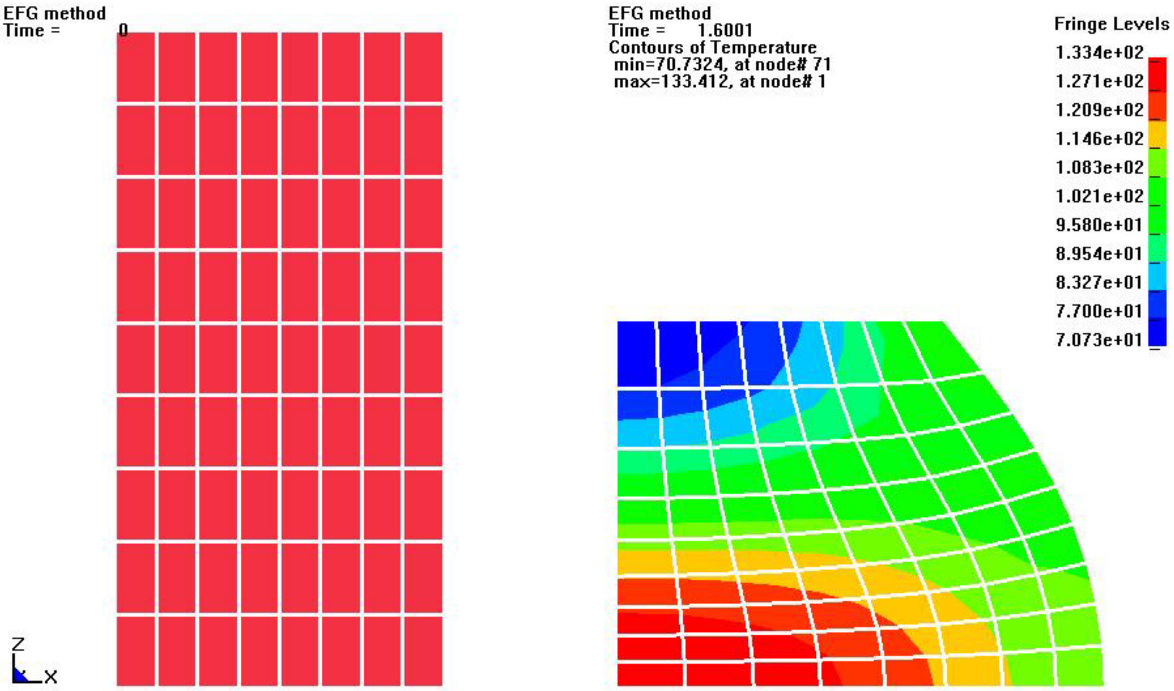

Figure 1: Side view of the eighth of the cylinder modelled for a 44% axial compression within 1.6s with EFG solid formulation. Due to plastic heating the temperature (C) rises (right).

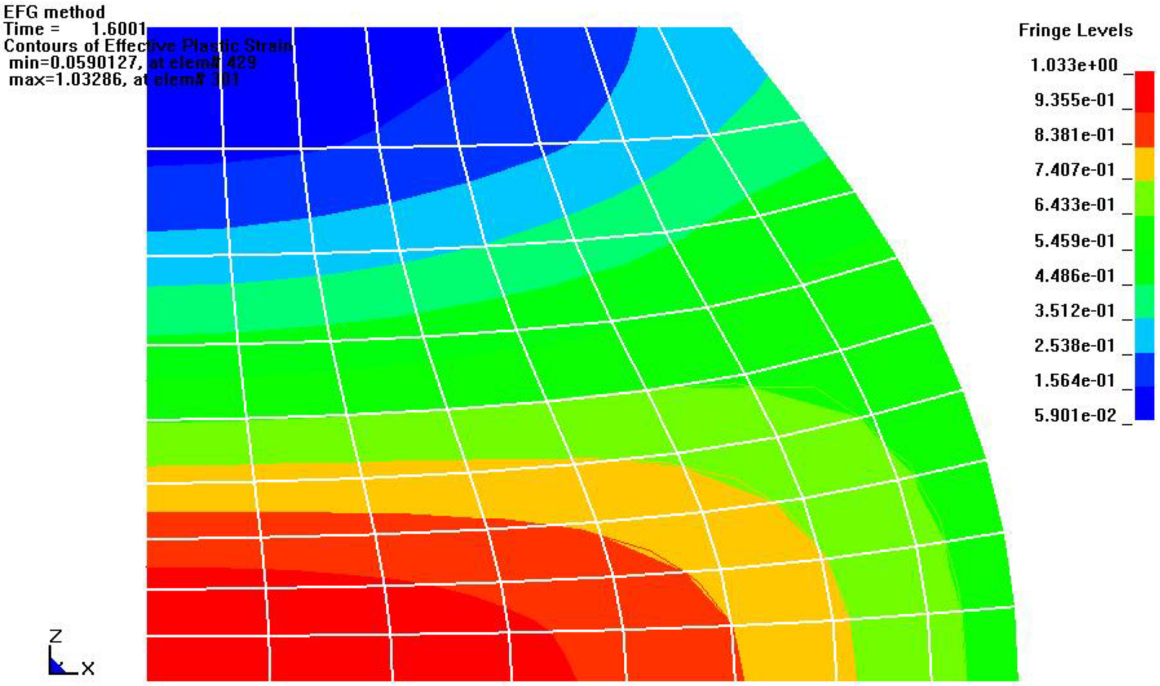

Figure 2: Plastic strain at the end of the forming process (EFG method).

3 Results

Figure 1 shows the principal course of the experiment. The center of the sample reaches a temperature of about 130C due to plastic heating. The effective plastic strain was about 1.0 after a compression of 44% in 1.6s (Figure 2). The center radius of the sample widened by about 4mm.

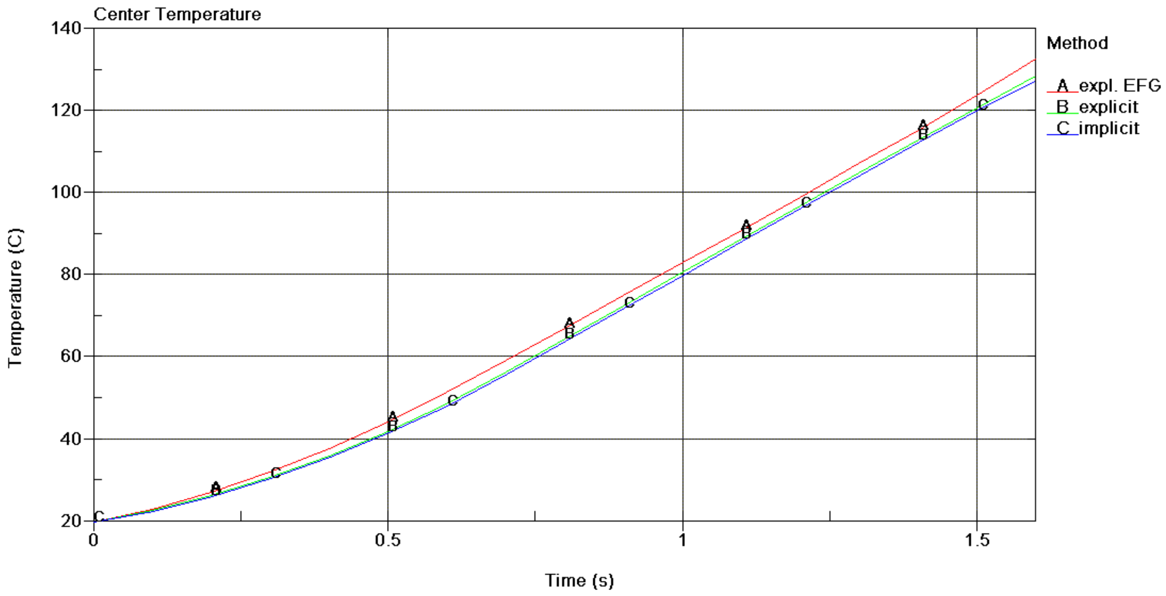

Figure 3: The predicted temperature rise in the center is slightly higher for EFG than for standard elements.

The 3D simulation in figure 1 was performed for default solid formulation (`ELFORM`=1, reduced integration) and explicit and implicit time integration of the mechanical field, and for an EFG solid formulation and an explicit integration. Hourglass control was set to type 6 on `*CONTROL_HOURGLASS` with default parameters, because the generated hourglass energy was smaller than for type 4. The ratio of hourglass energy to internal energy was 0.07. EFG does not need hourglass control. Selective reduced integrated and fully integrated solids (`ELFORM`=2 or 3) showed volume locking. Figures 3-5 compare the temporal development of the temperature, effective plastic strain and the widening of the sample. The results for explicit and implicit simulations with reduced integration are nearly identical. This proofs that the mass scaling has no influence. Note that 970.5434 and 3858 EFG solutions are different. The 5434 solution is slightly softer than the standard solution. Figure 4 shows the higher radial deformation. The effective plastic strain depicted in figure 5 is comparable. The computation times were 16s explicit, 32s implicit, and 428s EFG. An EFG calculation does not really pay off in this case. It might be an advantage that EFG does not require to introduce non-physical energy for hourglass stabilization while not being prone to volume locking. Therefore the estimated amount of plastic heating work may be more accurate and the prediction for the temperatures shown in figure 2 may be better. This could not be checked, because LS-DYNA does not allow putting out the amount of heat stored or the total plastic deformation work done.

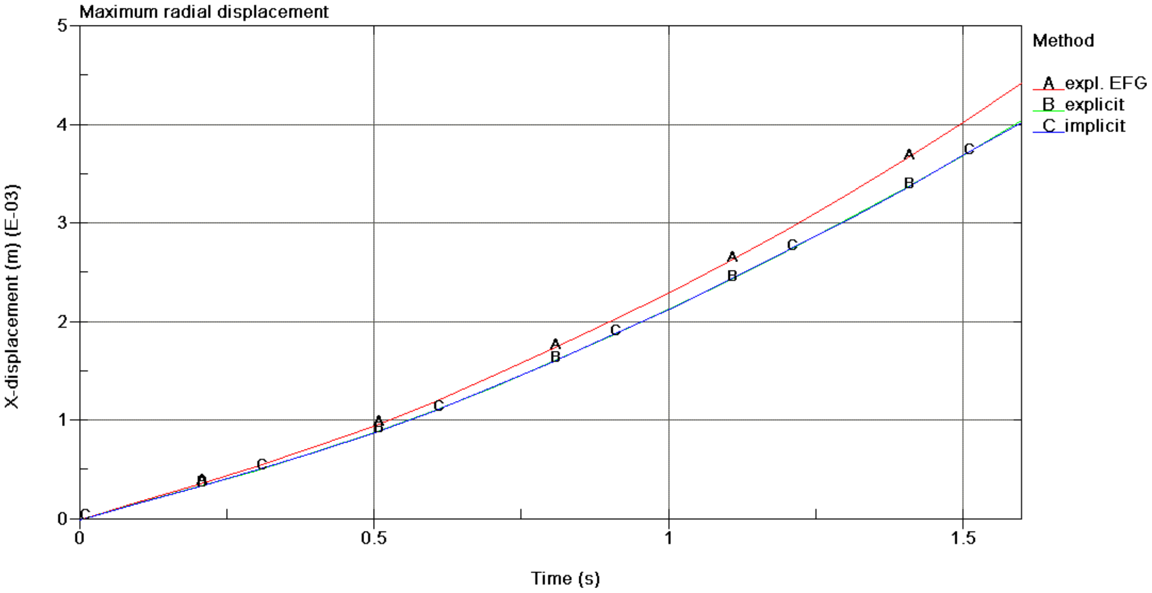

Figure 4: The predicted radial deformation in the center plane of the sample is higher for EFG than for standard elements.

3.1 Robustness against element distortion

In a second numerical experiment the compression was continued beyond 1.6s until a compression of 99% or the solver run aborts. This was done to test the robustness against element distortion of the element formulation.

The solver can abort in the mechanical or the thermal simulation part. It is possible to test this by switching to a pure mechanical solution on `*CONTROL_SOLUTION`. The pure mechanical simulation is remarkably robust and 99% compression is reached with explicit, implicit and EFG method.

The LS-DYNA EFG method has no influence on the thermal solution. The thermal simulation seems to be dependent on the background mesh. This process is more robust, if the thermal integration is set to one Gauss point (`GPT` on `*CONTROL_THERMAL_SOLVER`). Note that some warnings due to the forthcoming solver abortion do not appear in the `messag` or `d3hsp` file, but solely in the solver output! The thermal solution with adaptive time step stopped because the minimum thermal time step is reached. If this is turned off (`TS` on `*CONTROL_THERMAL_TIMESTEP`) the simulation with one point thermal integration reaches 99% compression, too. Therefore, solver abortion is not a good criterion to assess robustness of EFG in this example.

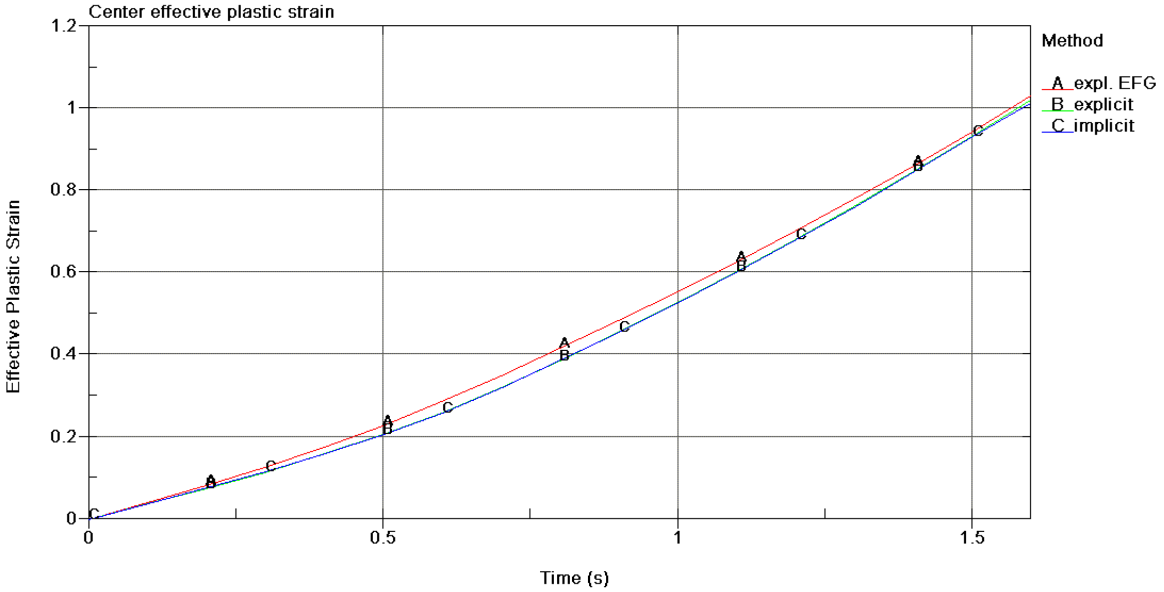

Figure 5: Comparison of the effective plastic strain in the center element predicted with three methods.

4 Conclusions

T.C. Wu [4] advices to start out with the normal element formulation and only switch to EFG, if something goes wrong and the solver aborts. The results in this paper support this. Coupled thermal-mechanical simulations with EFG solids are possible in LS-DYNA. The EFG method allows avoiding non-physical energy for hourglass stabilization while not being prone to volume locking. The prediction of the plastic heating heat may be more accurate. The CPU time is much higher for EFG in the current implementation. Even compared to implicit solutions there is a performance lack of factor 10. For the examples in this paper the results with EFG shows a slightly softer behaviour. When axisymmetric, implicit and adaptive EFG is implemented in LS-DYNA this numerical experiments should be repeated.

5 References

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[4] Wu, C.T., Element Free Galerkin (EFG) Method in LS-DYNA, Seminar notes LSTC, 2004
[5] N.N., Thermal course, www.dynaexamples.com
[6] supplementary material published on www.rudolf-boetticher.de
[7] Chin, J.Y., Lee, S.W., Paik, S.H. and Chung, W.S. , The Effects of Numerical Result and Computing Time Due to Mass Scaling in Rolling Analysis, 8. International LS-DYNA Users Conference, 2004

Abstracted input file

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*TITLE

*NODE
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*ELEMENT_SOLID
       1       1      21      32      43      20     163     323     395     155
*SECTION_SOLID
         1         1
*MAT_PIECEWISE_LINEAR_PLASTICITY
         1 0.783E+04 0.210E+12  0.280000  0.00      0.00      0.00
  0.00      0.00      1.00      0.00

*DEFINE_CURVE
         1         0     1.000     1.000     0.000     0.000
  0.000000000000E+00  2.500000000000E+08
  1.000000000000E-02  2.800000000000E+08
  2.000000000000E-02  3.000000000000E+08
  5.000000000000E-02  3.500000000000E+08
  1.000000000000E-01  4.200000000000E+08
  2.000000000000E-01  5.000000000000E+08
  4.000000000000E-01  5.200000000000E+08
  5.000000000000E+00  5.400000000000E+08
*DEFINE_CURVE
         2         0     1.000     1.000     0.000     0.000
  0.000000000000E+00  0.000000000000E+00
  1.600000000000E+00 -7.920000000000E-03
  1.000000000000E+01 -7.920000000000E-03
*SET_NODE_LIST
         1     0.000     0.000     0.000     0.000
        62        63        64        65        66        67        68        69
*BOUNDARY_PRESCRIBED_MOTION_SET
         1         3         2         2     1.000         0 0.000     0.000
*SET_NODE_LIST
         2     0.000     0.000     0.000     0.000
         1
*BOUNDARY_SPC_SET
         2         0         1         1         1         0         0         0
*SET_NODE_LIST
         3     0.000     0.000     0.000     0.000
         2         3         4         5         6         7         8         9
*BOUNDARY_SPC_SET
         3         0         0         1         1         0         0         0
*SET_NODE_LIST
         4     0.000     0.000     0.000     0.000
        10        11        12        13        14        15        16        17
*BOUNDARY_SPC_SET
         4         0         1         0         1         0         0         0
*SET_NODE_LIST
         5     0.000     0.000     0.000     0.000
        18        19        20        21        22        23        24        25
*BOUNDARY_SPC_SET
         5         0         0         0         1         0         0         0
*SET_NODE_LIST
         6     0.000     0.000     0.000     0.000
        62        63        64        65        66        67        68        69
*BOUNDARY_SPC_SET
         6         0         1         1         0         0         0         0
*SET_NODE_LIST
         7     0.000     0.000     0.000     0.000
       123       124       125       126       127       128       129       130
*BOUNDARY_SPC_SET
         7         0         1         0         0         0         0         0
*SET_NODE_LIST
         8     0.000     0.000     0.000     0.000
       131       132       133       134       135       136       137       138
*BOUNDARY_SPC_SET
         8         0         0         1         0         0         0         0
```

```
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addendum.k
*END
```

Listing of addendum.k

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*CONTROL_HOURGLASS
6
*CONTROL_ENERGY
2
*CONTROL_TERMINATION
$slightly more to get all data written in implicit
1.6001
$insert here appropriate DATABASE_* statements
*CONTROL_EFG
$0,1 DILA=1 may be necessary in post ver. 3858

$*PART $Part          1 for Mat         1 and Elem Type         1
$1,1,1,0,0,0,0,1
1,2,1,0,0,0,0,1
*SECTION_SOLID_EFG
2,41

*CONTROL_SOLUTION
2
*CONTROL_THERMAL_SOLVER
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*CONTROL_TIMESTEP
        0.        0.         0        0.    1.e-04
*CONTROL_THERMAL_TIMESTEP
1,1.,1.E-4,1.E-4,0.01
*MAT_THERMAL_ISOTROPIC
         1     7830.
      460.       46.
*SET_NODE_GENERAL
999
ALL
*INITIAL_TEMPERATURE_SET
999,20.
*END
$at the moment EFG cards and IMPLICIT card are not allowed being
$in the same deck. If you comment out the previous *END you must
$comment out the two EFG cards in the beginning
$
*CONTROL_IMPLICIT_GENERAL
         0    0.0001         0         0         0
*CONTROL_IMPLICIT_AUTO
         1         0         0    0.0001      0.01
$*CONTROL_IMPLICIT_DYNAMICS
$may help for convergence
$1
*END
```