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# Meshing of Solid Conductor Regions Modeled by Surface Impedance for Accurate Results in the Finite Element Analysis of a Cold Crucible Furnace

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**Abstract.** The paper deals with the meshing in the finite element Flux3D models where the surface impedance formulation of the electromagnetic field is used for the solid conductor regions. This meshing is able to ensure a good accuracy of the numerical solution for reasonable memory requirements and computation time. The Joule losses, voltages and powers in a cold crucible induction furnace without charge for glass melting are evaluated

Keywords: cold crucible furnace, finite element analysis, surface impedance, computation domain meshing

## 1. Introduction

The penetration depth of the electromagnetic field in electro-conductive regions/volumes, called also skin depth, is a key parameter in induction heating applications, since the most of the Joule power/losses are concentrated in this skin depth volume including the outer surface of the region. The finite element meshing in the depth of the metallic regions must be correlated with the correspondent skin depth values when the  $\mathbf{A} - \mathbf{V}$  or  $\mathbf{T} - \Omega$  volume formulations of the electromagnetic field are used in the regions of solid conductor type. The values associated to the mesh lines or mesh points entities must be lower than the skin depth values.

For the cold crucible induction furnace studied in this paper, Fig. 1 a), b), which operates without charge at the frequency 300 kHz, the values of the skin depth are 0.18 mm in the copper of the inductor and 0.81 mm in the stainless steel of all other metallic parts of this device. These values being so small in comparison with the dimensions of the correspondent regions, the electromagnetic field can be considered virtually non-existent inside these regions. The computation of the electromagnetic field in problems with such regions takes into account only the outer surface of these solid conductor regions through a particular boundary condition called Surface Impedance. This condition considers implicitly the correspondent skin depth values.

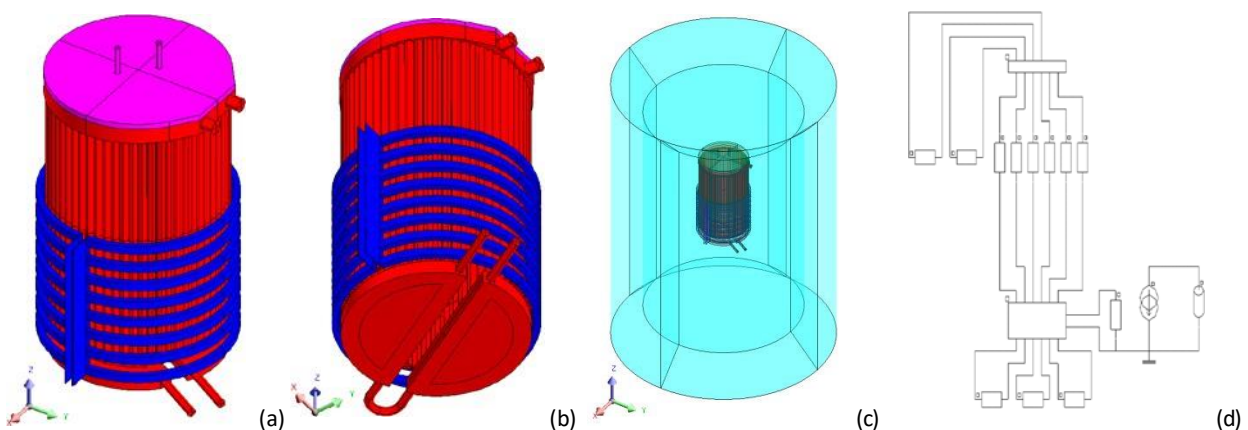


Fig. 1. Cold crucible furnace geometry, finite element computation domain and the associated electric circuit

With the Surface Impedance formulation of the electromagnetic field for regions of solid conductor type it is not compulsory that the meshing of the computation domain be so fine like in the  $\mathbf{A} - \mathbf{V}$  or  $\mathbf{T} - \Omega$  volume formulations in such regions. Thus, the correspondent finite element models are very advantageous in terms of memory requirements and computation time. This paper is focused on the establishment of an appropriate meshing of the finite element computation domain, Fig. 1 c), including the studied cold crucible furnace, with all metallic components modelled as Surface Impedance regions. It is a meshing that realises a compromise between the accuracy of the numerical results, the memory requirements and the computation time.

## 2. Finite element Flux3D models of an induction cold crucible furnace. Meshing and accuracy of the numerical result

The 3000 A - 300 kHz electric supply of the furnace in Figure 1 generates high values of Joule power in the cold crucible, in the furnace bottom and in the furnace inductor. Through the associated circuit model in the Figure 1 d), the voltage of the inductor supply, voltages between the water cooling connectors, voltages between the two boxes of the bottom, Fig. 1 b), and between the bottom and the cold crucible are evaluated.

The images in Fig. 2 reflect the meshing of the main regions of the computation domain – the inductor, the bottom and a part of the furnace cold crucible tubes. The meshing of the computation domain is defined in Flux3D through the MeshPoint and MeshLine entities. Defining values of these entities in decreasing order for the applications with first order elements Mord1\_1, Mord1\_2, Mord1\_3 and Mord1\_4 in Table 1 and M1, M2, M3 and M4 in Table 2 for second order elements, it was found the meshing configurations that offer accurate enough numerical results. In the Tables 3 and 4 are presented the numbers of the meshing nodes and volume elements in entire computation domain, the memory of the solved numerical application on the computer disk and the computation time.

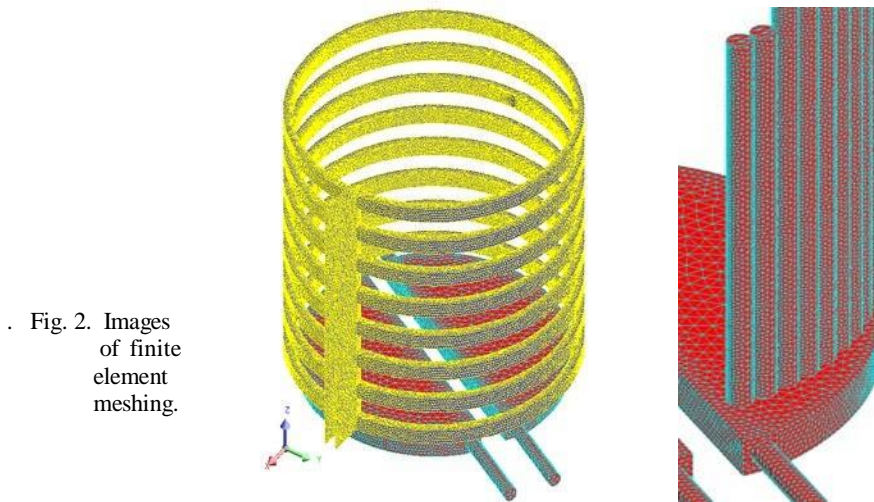


Table 1. MeshPoints and MeshLines in [mm] for first order element applications

Application	Inductor		Cold crucible tubes			Bottom
	Int	Ext	In-between	Ext	Int	
Mord1_1	4.0	8.0	4.0	8.0	8.0	8.0
Mord1_2	3.0	5.0	3.0	6.0	6.0	6.0
Mord1_3	2.2	4.5	2.2	3.6	4.6	3.2
Mord1_4	1.8	4.4	2.0	3.0	4.5	2.5

Table 2. MeshPoints and MeshLines in [mm] for second order element applications

Application	Inductor		Cold crucible tubes			Bottom
	Int	Ext	In-between	Ext	Int	
M1	6.0	12.0	6.0	11.0	13.0	12.0
M2	5.0	11.0	5.0	9.0	12.5	10.0
M3	4.0	8.0	4.0	8.0	9.0	8.0
M4	3.0	7.0	3.0	7.0	9.0	7.0

Table 3. Number of nodes and volume elements, memory requirements and computation time for the first order element applications

Application	Number of nodes	Number of volume elements	Solved application memory [GB]	Computation time [min]
Mord1_1	670463	3946070	8.69	40
Mord1_2	1320776	7775468	17.6	96
Mord1_3	2479606	14526208	33.5	564
Mord1_4	<b>3071351</b>	17970198	38.6	600

Table 4. Number of nodes and volume elements, memory requirements and computation time for the first the second order element applications

Application	Number of nodes	Number of volume elements	Solved application memory [GB]	Computation time [min]
M1	2088437	1556697	13.4	115
M2	<b>3068365</b>	2288785	20.6	212
M3	5060563	3776963	34.1	420
M4	6811575	5077319	46.0	645

Tables 5 and 6 contain numerical results of applications with different meshing for important quantities associated with the cold crucible furnace operation. Since the meshing finesse increase, the differences between the results in the second and in the first row, between the results in the third row and in the second row and between the results in the last row and in the third row decrease. The evolution of the results related inductor losses, cold crucible losses and bottom losses with the meshing refinement are presented in Figure 3 for first order elements and in Figure 4 for second order elements. The results of the last applications, Mord1\_4 and M4 respectively are considered accurate enough from numerical point of view because they differ less than 0.89 % from the previous Mord1\_3 and M3 results.

Table 5. Main results of first order elements applications

Application	Inductor voltage [V]	Furnace reactive power [kVAr]	Inductor Joule losses [kW]	Crucible Joule losses [kW]	Furnace bottom losses [kW]	Bottom induced voltage [V]
Mord1_1	1796.93	5389.5	5.860	90.931	18.292	581.98
Mord1_2	1793.40	5378.8	6.150	96.067	18.809	581.65
Mord1_3	1821.45	5462.9	6.538	101.50	20.011	586.06
Mord1_4 (Mord1_4-Mord1_3)/ Mord1_3 * 100	1805.27 - 0.8883%	5415.8 - 0.8622%	6.570 + 0.4894%	101.37 - 0.1281%	20.065 + 0.2699%	583.05 - 0.514%

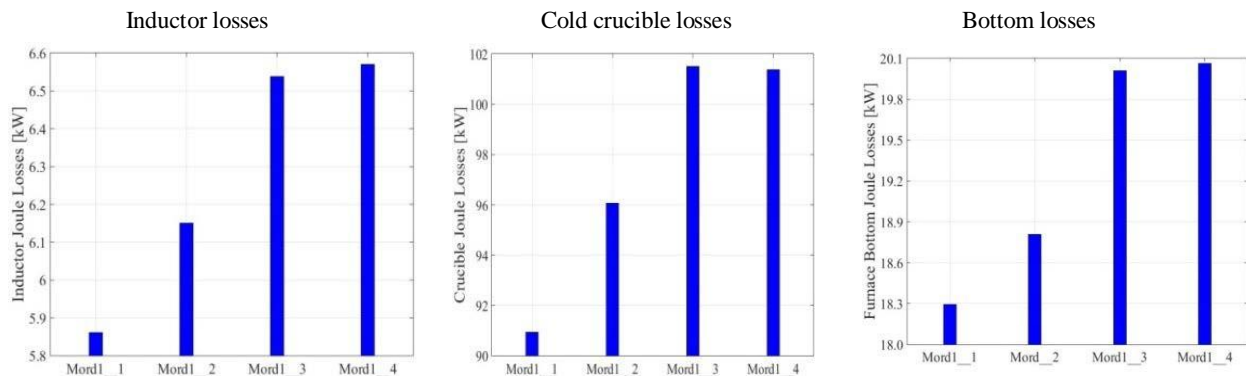


Fig. 3. Inductor, cold crucible and bottom losses evolution with meshing refinement – first order elements applications

The most important finding of this paper section is based on the comparison of the computation data in the last rows of Table 1 (Mord1\_4) and Table 2 (M4) and the values of the copper and stainless steel penetration depth. The minimal dimensions associated with the points and lines meshing on surfaces of the solid conductor regions in case of Surface Impedance formulation are much higher than the correspondent skin depths.

Table 6. Main results of second order elements applications

Application	Inductor voltage [V]	Furnace reactive power [kVAr]	Inductor Joule losses [kW]	Crucible Joule losses [kW]	Furnace bottom losses [kW]	Bottom induced voltage [V]
M1	1804.34	5411.6	6.609	96.06	20.383	587.22
M2	1799.60	5397.3	6.705	100.59	20.540	586.21
M3	1793.89	5379.9	6.850	106.32	20.864	585.23
M4	1793.20	5377.9	6.917	106.51	21.007	585.47
(M4-M3)/M3*100	- 0.038%	- 0.037%	+ 0.978%	+ 0.179%	+ 0.685%	- 0.041%

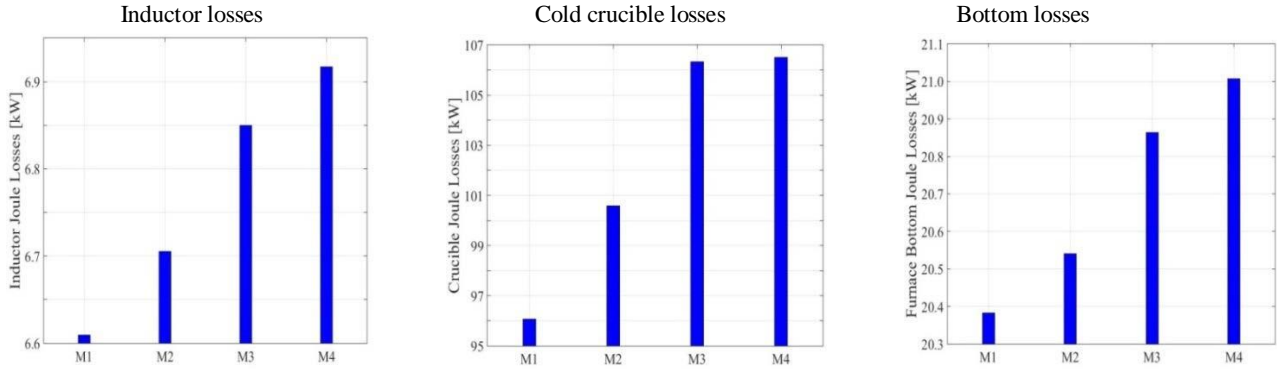


Fig. 4. Inductor, cold crucible and bottom losses evolution with mesh refinement – second order elements applications

### 3. Experimental results

The experimental cold crucible in Figure 5, whose geometrical dimensions and physical properties are the input data of the finite element applications previously described was supplied with the current 2880 A from a frequency converter with the output frequency 298 kHz, values which are slightly different from the computation data 3000 A and 300 kHz. The experimental measured values: supply voltage 1950 V, cold crucible losses 103 kW and bottom losses 20.4 kW are in accordance with the finite element computation results in Tables 5 and 6.

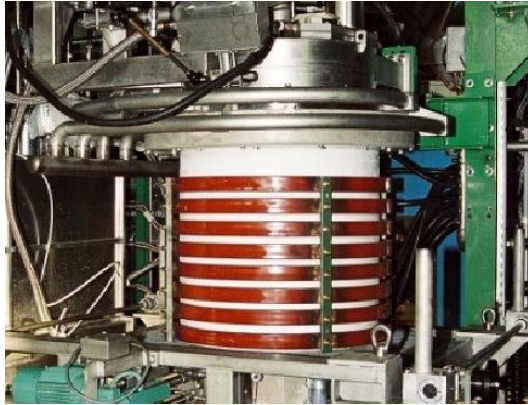


Fig. 5. Experimental cold crucible furnace

### 4. Results of two applications with first and second order elements

This section of the paper compares two applications Mord1\_4, with first order elements and M2, with second order element, Table 7, with practically the same number of nodes. These two applications are characterized by almost the same number of unknowns, Table 7, but the number of volume elements is around 8 times much higher in case of the first order elements application, Table 8. The computation time is almost 3 times higher and the memory requirements almost two times higher. Excepting the Joule losses in the inductor and in the furnace bottom, the main results of the two applications, Table 9, differs each other less than 0.77 %. It must be noticed that the second order application M2 has a coarse meshing in comparison with the M4 application, those that offers the accurate numerical results for the second order elements. That should be the reason of the difference over 2 % in Table 9. However, for similar results accuracy, the applications with second order elements are advantageous in terms of computation time and memory requirements.

Table 7. MeshPoints and MeshLines of two applications ord1 and ord2

Meshing	Inductor MeshPoints [mm]		Cold crucible tubes MeshLines [mm]			Bottom MeshLine [mm]
	Int	Ext	In-between	Ext	Int	
Mord1_4, ord1	1.8	4.4	2.0	3.0	4.5	2.5
M2, ord2	5.0	11.0	5.0	9.0	12.5	10.0

Table 8. Number of nodes, of volume elements, memory requirements and computation time of two applications ord1 and ord2

Meshing	Number of nodes	Number of volume elements	Required storage memory [GB]	Computation time [min]
Mord1_4, ord1	3071351	17970198	38.6	600
M2, ord2	3068365	2288785	20.6	212

Table 9. Main results of two applications ord1 and ord2

Application	Inductor voltage [V]	Furnace active power [kW]	Furnace reactive power [kVAr]	Inductor Joule losses [kW]	Crucible Joule losses [kW]	Furnace bottom losses [kW]	Bottom induced voltage [V]
Mord1_4, ord1	1805	128.2	5416	6.570	101.4	20.07	583.1
M2, ord2	1780 - 0.32%	128.0 - 0.14%	5397 - 0.34%	6.704 + 2.06%	100.6 - 0.77%	20.54 + 2.37%	586.2 - 0.54%

Figure 5 contains zooms of the bottom meshing in the applications with the same number of nodes Mord1\_4 and M2.

Graphical results related the current density in the inductor, in the tubes of the cold crucible and in the furnace bottom are presented in Figs. 7, 8 and 9. The values of the maximum current density  $J_{max}$  and the relative difference between the Ord1 results of the Mord1\_4 application and the Ord2 results of the M2 application are included.

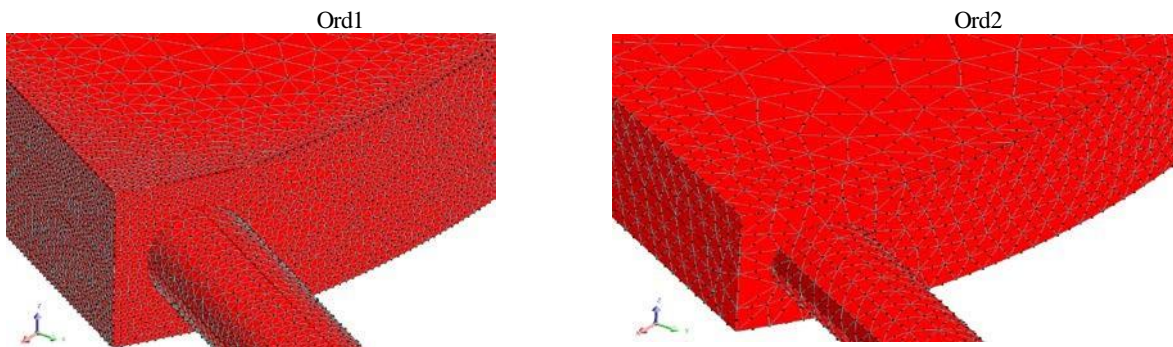


Fig. 6. Zooms of the bottom meshing

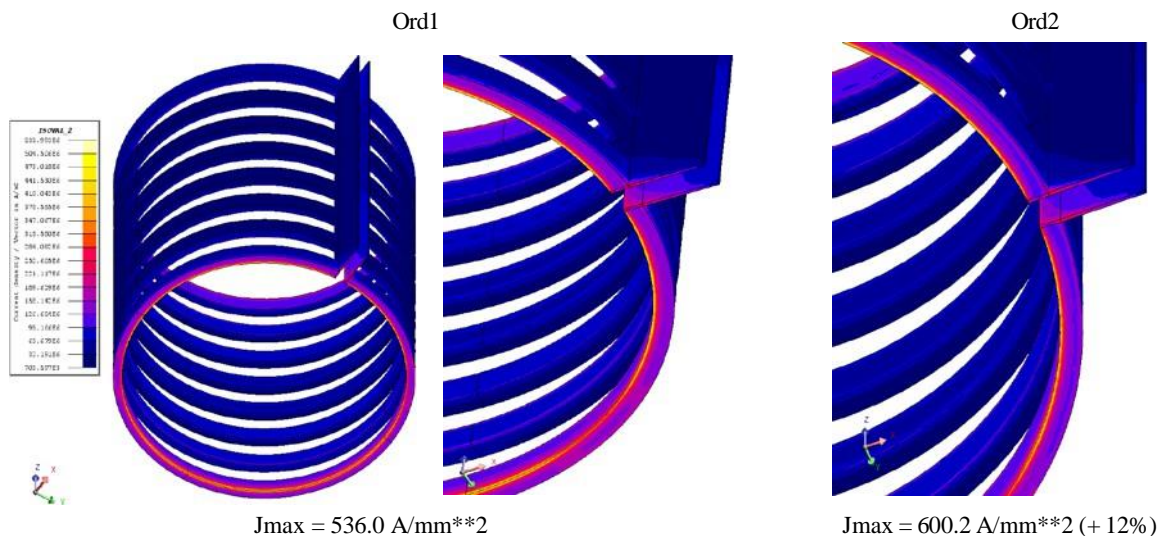


Fig. 7. Current density in the inductor region

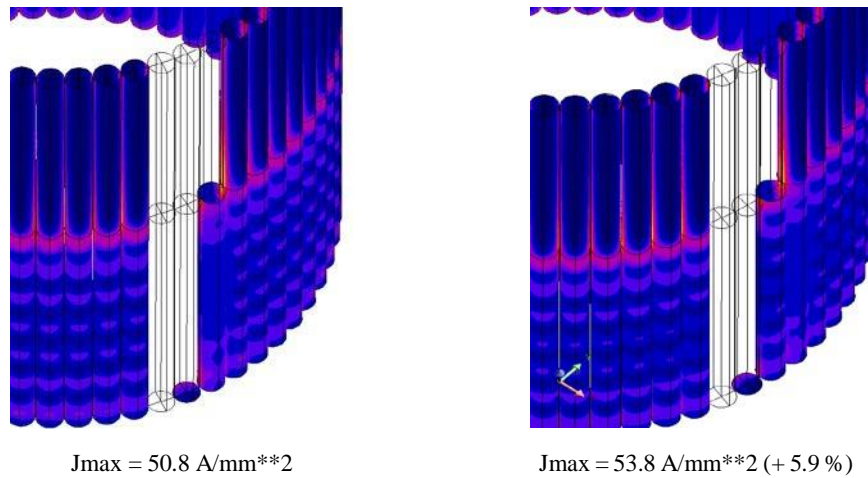


Fig. 8. Current density in the cold crucible tubes (zooms)

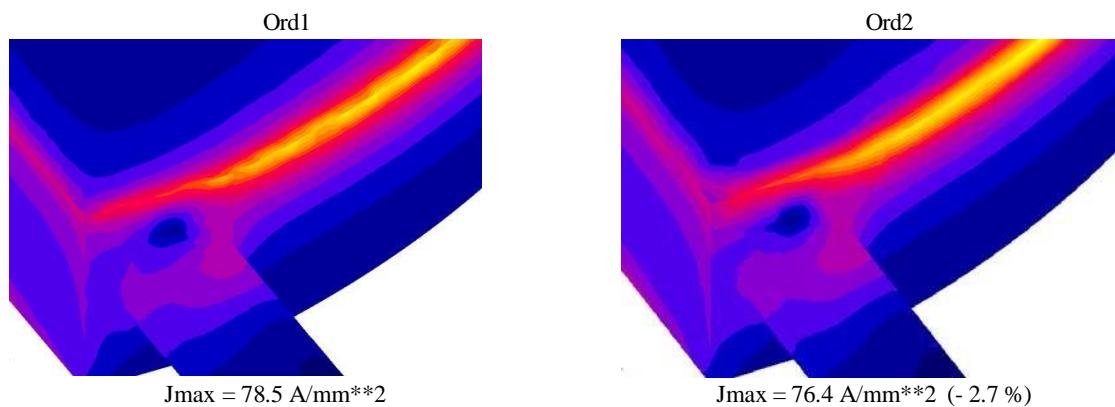


Fig. 9. Current density in the bottom region (zooms)

## 5. Conclusions and perspectives

The surface impedance formulation of the AC electromagnetic field in regions of solid conductor type takes possible finite element solutions for relatively complex configurations of the computation domain by using a relatively coarse mesh. Such a mesh is not so fine like when the  $\mathbf{A} - \mathbf{V}$  or  $\mathbf{T} - \Omega$  formulations are used in solid conductor regions, where the minimum values of the mesh lines and/or mesh points are under the values of the penetration depth in these regions.

The method proposed in this paper for the choice of the minimum values of the MeshLines and MeshPoints is based on the evaluation of the accuracy of numerical results for successive levels of meshing refinement. In problems with different solid conductor regions such a coarse meshing must be defined so that the increase of the minimum values of the lines and points meshing with respect the correspondent penetration depths must be more or less similar.

Since for the same number of nodes, the number of volume elements in case of first order elements - is much higher than in case of second order elements - 7.85 times in the applications in this paper, the computation time and the memory requirements are much higher in the case of first order element. Consequently, the second order finite element solutions are much more convenient.

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