ICENTE'20

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Verification of Oxygen Free High Purity Copper Bar Computational Impact Analysis with Hawkyard Energy Approach

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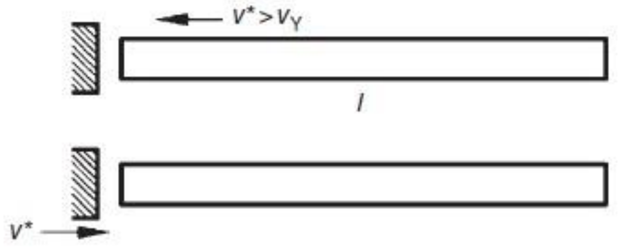
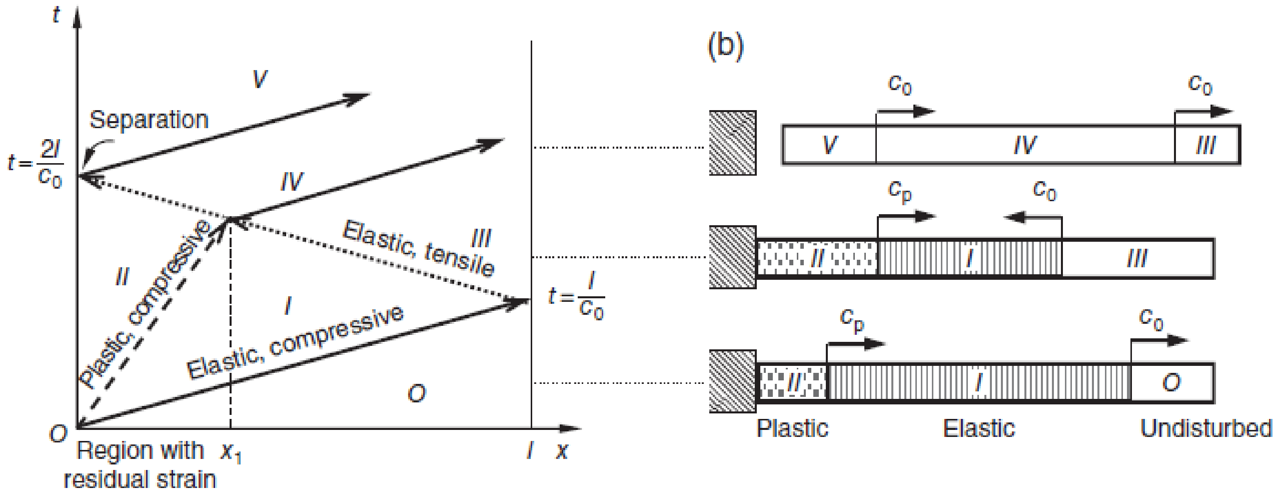
Contents

- Analytical Deformation Methods for Impact Analysis
- Hawkyard’s Energy Approach
- Computational Impact Analysis
- Literature Data
- Model Verification
- Conclusions

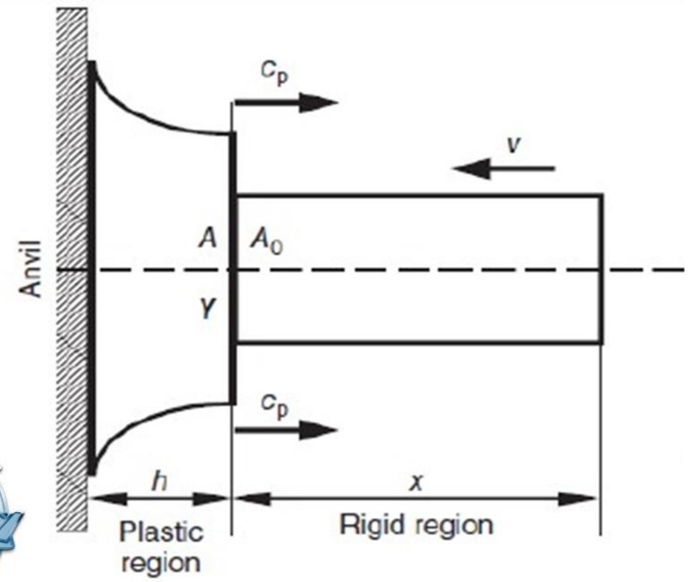
Analytical Deformation Methods

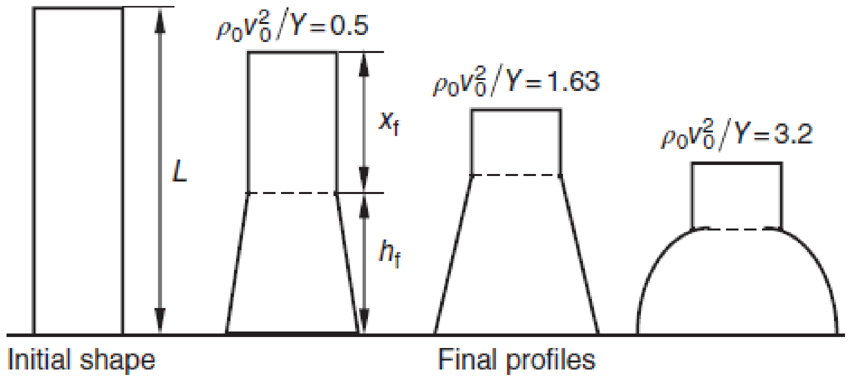
Lensky's 1D Model, 1949.





Taylor's Approach, 1948.

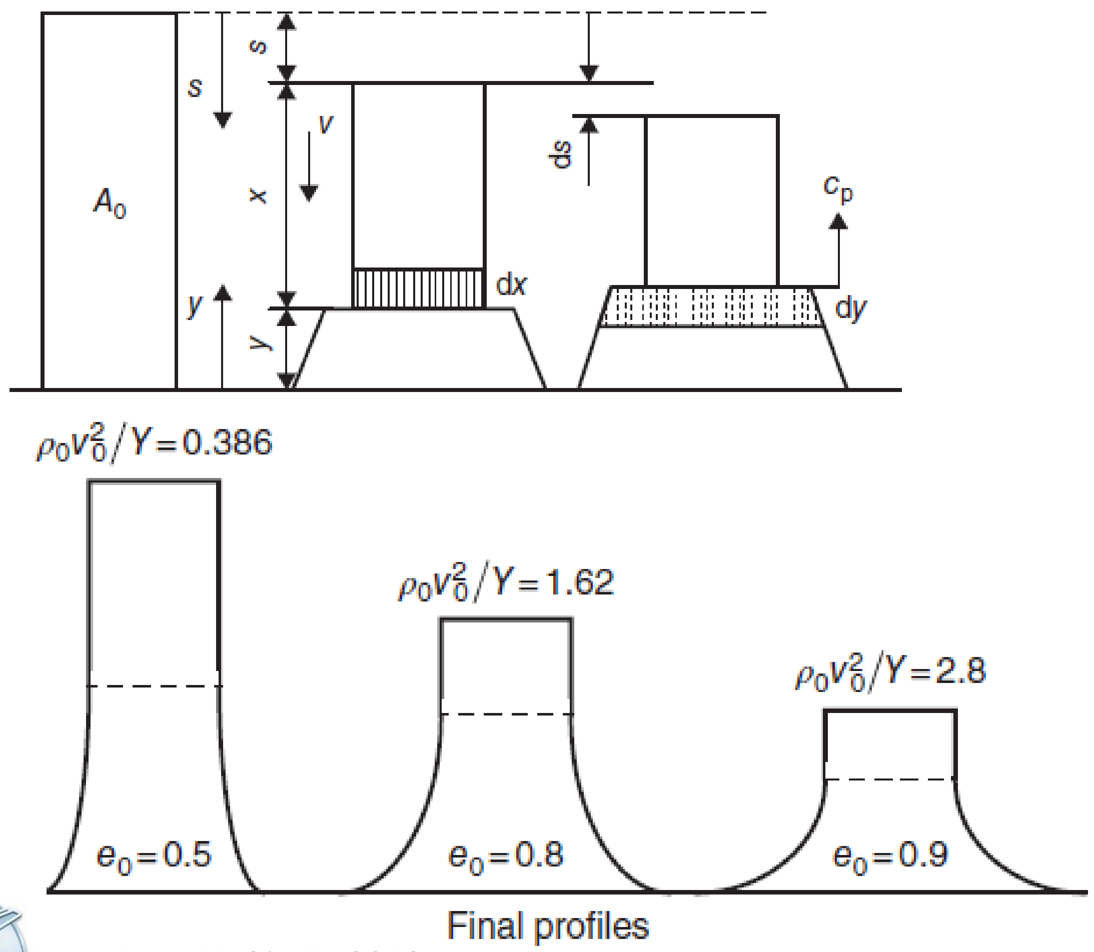




Rao, L.R. *et al*, Applied Impact Mechanics, 2016.

Analytical Deformation Methods

Hawkyard's Approach, 1969.



Yu, T. X. Qiu X., 2018.

Rao, L.R. *et al*, Applied Impact Mechanics, 2016.

- The continuity equation, definition of plastic strain, and definition of plastic wave speed are kept as same as in Taylor's approach:

$$A_0(v + c_p) = Ac_p \qquad e = 1 - \frac{A_0}{A} \qquad c_p = \frac{A_0}{A - A_0}v = \frac{1-e}{e}v$$

- Energy dissipation rate for crossing the plastic front and rate of loss in the KE of the projectile are introduced accordingly:

$$\frac{dw}{dt} = A_0(v + c_p)Y ln\frac{A}{A_0} \qquad \frac{dE}{dt} = A_0 v\left[\frac{1}{2}\rho_0 v(v + c_p)Y\right]$$

- Energy conservation at any time requires that the rate of loss in KE of projectile is equal to the energy dissipation rate for crossing the plastic front. For mushrooming:

$$\frac{\rho_0 v^2}{Y} = 2\left[ln\left(\frac{1}{1-e}\right) - e\right] = 2\left[\ln\left(\frac{A}{A_0}\right) - \left(1 - \frac{A_0}{A}\right)\right]$$

- The equation of motion for the rigid segment:

$$YA_0 = -\rho_0 A_0 x\left(v\frac{dv}{ds}\right)$$

- Final length of the rigid region:

$$x_f = (1 - e_0)L_0$$

- Using plastic strain, the deformed diameter of copper bar: $\frac{A}{A_0} = \left(\frac{1}{1-e}\right)$

Computational Impact Analysis

<u>Specifications of the Taylor Bar</u>:

Initial length of the cylinder: L_0= 25.4 (10^{-3}) m

Initial diameter of the cylinder: D_0= 7.6 (10^{-3}) m

Density: 8930 kg/m^3

Yield stress (Y): 314 (10^6) Pa

Impact velocity: 190 m/s

Mesh density: from 0.2 to 0.5

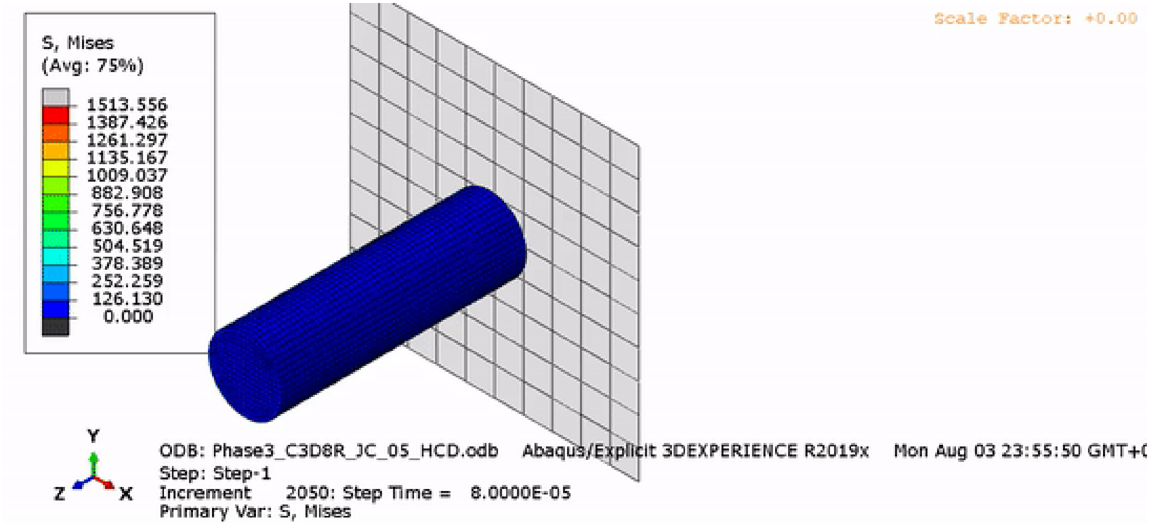
Mesh type: C3D8R and CAX4R (Combined and Default mode hour glass control)

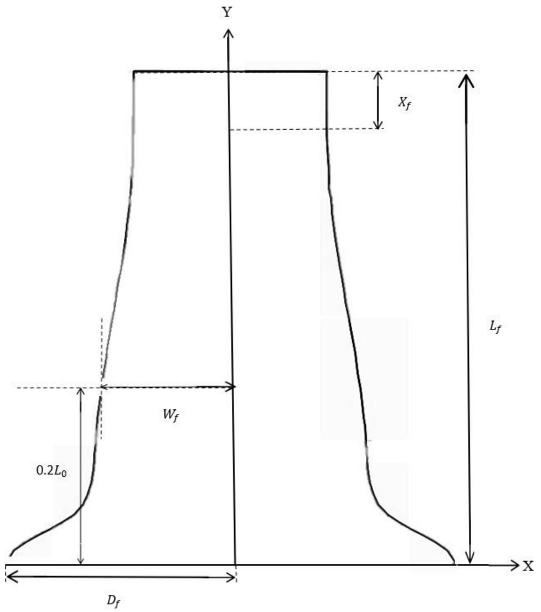
Material model: (1) von Mises Elastic Perfectly Plastic

(2) Johnson-Cook Plasticity

Duration: 80µs

Abaqus Explicit v6.19 Intelcore i5 2.4 G.Hz 4 GB ram





Johnson's expression

$$\bar{\Delta} = \frac{1}{3}\left(\frac{|\Delta L|}{L} + \frac{|\Delta D|}{D} + \frac{|\Delta W|}{W}\right)$$

Literature Data

Ma, S. and Zhang, X (2007) performed SPH, FEM, and MPM to simulate the impact of a copper cylinder to a rigid wall with an impact velocity of 190 m/s to compare their accuracy and efficiency.

The Johnson-Cook material model is used. The simulation time is 80μs, when the kinetic energy reaches zero.

Performances of MPM, SPH and FEM are investigated numerically by using MPM3D code and LS-DYNA.

Table-1: Numerical results obtain in Taylor bar impact simulation

Method	L (mm)	D (mm)	W (mm)	$\bar{\Delta}$
Test	16.2	13.5	10.1	-
SPH1	15.4	15.6	9.9	0.075
SPH2	15.5	14.7	10.0	0.047
MPM	16.3	13.0	9.6	0.031
FEM1	16.3	13.2	10.1	0.009
FEM2	16.3	13.2	10.1	0.009

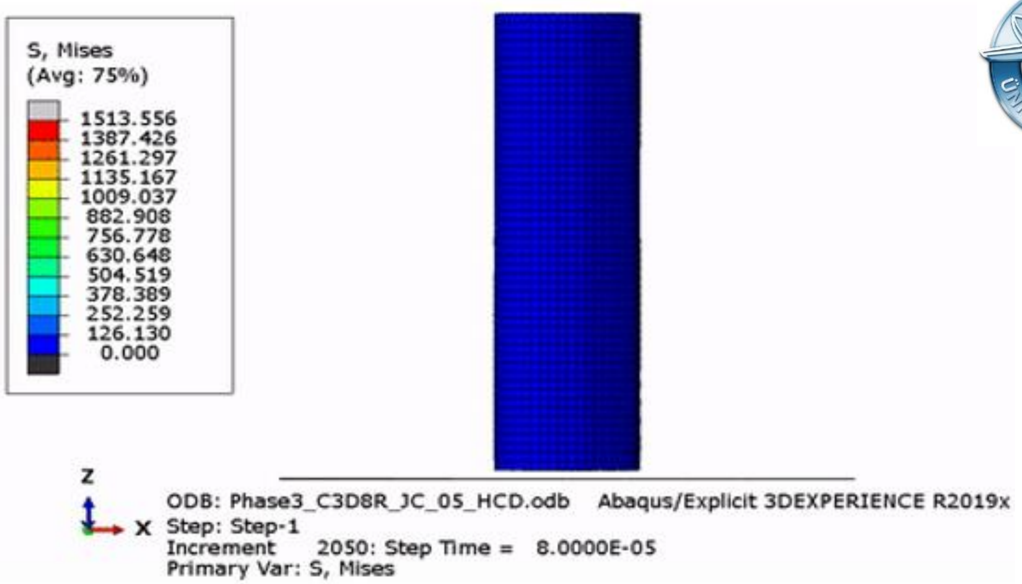
Table-2: Computational cost in Taylor bar impact simulation

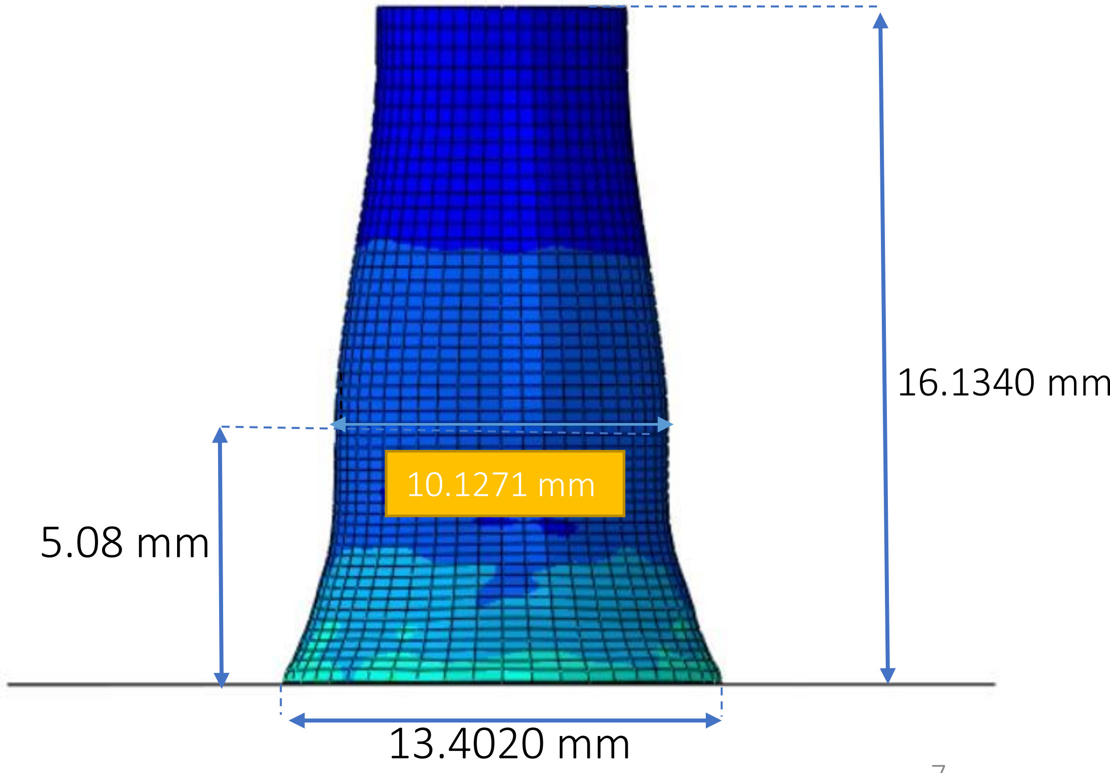
Method	Processor Time (s)	Wall Clock Time (s)
SPH1	172	179
SPH2	204	209
MPM	78	79
FEM1	693	699
FEM2	116	119

Results

Element Size	0.2				0.3				0.4				0.5			
Material Model	Von Mises Elastic, Perfectly Plastic		Johnson-Cook		Von Mises Elastic, Perfectly Plastic		Johnson-Cook		Von Mises Elastic, Perfectly Plastic		Johnson-Cook		Von Mises Elastic, Perfectly Plastic		Johnson-Cook	
Mesh Type	C3D8R		C3D8R		C3D8R		C3D8R		C3D8R		C3D8R		C3D8R		C3D8R	
Hourglass Control	C*	D*	C*	D*	C*	D*	C*	D*	C*	D*	C*	D*	C*	D*	C*	D*
Analysis No	1	2	17	18	3	4	19	20	5	6	21	22	7	8	23	24
Status	C**	C**	C**	C**	C**	C**	C**	C**	C**	C**	C**	C**	C**	C**	C**	C**
Max Von Mises (MPa)	314.000	314.057	3346.839	3049.586	314.000	314.000	3271.490	3452.077	314.000	314.000	1309.234	2013.363	314.000	314.000	1415.702	1513.556
U_{1max} (mm)	5.445	11.364	3.174	3.230	9.178	5.494	2.778	3.144	5.907	5.358	2.891	2.940	5.935	5.452	2.591	2.901
U_{1min} (mm)	-8.661	-17.670	-2.785	-2.658	-8.550	-5.377	-3.179	-2.815	-5.760	-5.408	-3.032	-2.904	-5.917	-5.525	-2.847	-2.822
U_{2max} (mm)	6.524	14.318	3.274	3.052	8.142	5.519	2.790	2.863	6.233	5.328	3.018	2.797	5.882	5.475	2.625	2.892
U_{2min} (mm)	-5.814	-13.325	-2.694	-2.777	-8.952	-5.388	-3.160	-3.065	-5.779	-5.318	-2.873	-2.905	-5.973	-5.439	-2.686	-2.830
U_{3max} (mm)	2.309	6.691	0	0	5.902	1.692	0	0	2.397	2.005	0	0	2.916	4.409	0	0
U_{3min} (mm)	-9.267	-9.596	-9.018	-9.551	-10.351	-8.992	-9.465	-9.471	-9.720	-8.950	-9.625	-9.550	-9.586	-9.349	-9.394	-9.266
Average Error	0.1770	0.3335	0.0153	0.0226	0.2449	0.1752	0.0194	0.0177	0.1723	0.1628	0.0178	0.0154	0.1704	0.1488	0.0158	0.0047
Total CPU Time (s)	20,5	20	20,1	20,2	3,8	6,2	6,3	3,6	1,5	1,5	2,6	2,5	1,4	0,8	1,5	1,5
Wall Clock Time (s)	20	20	20	20	4	6	7	3	1	2	3	3	2	1	1	2

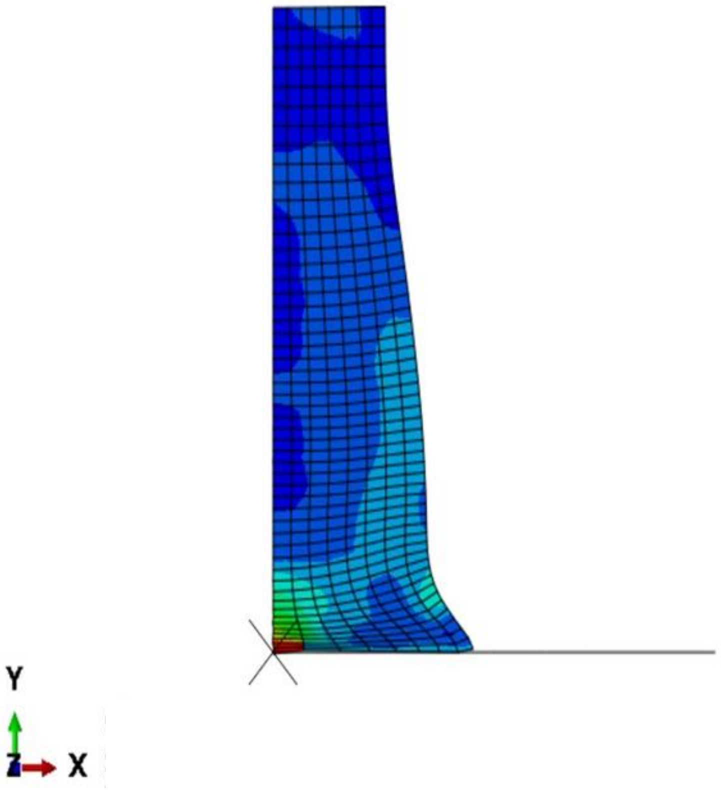
C*:Combined D*:Default C**:Completed





Results

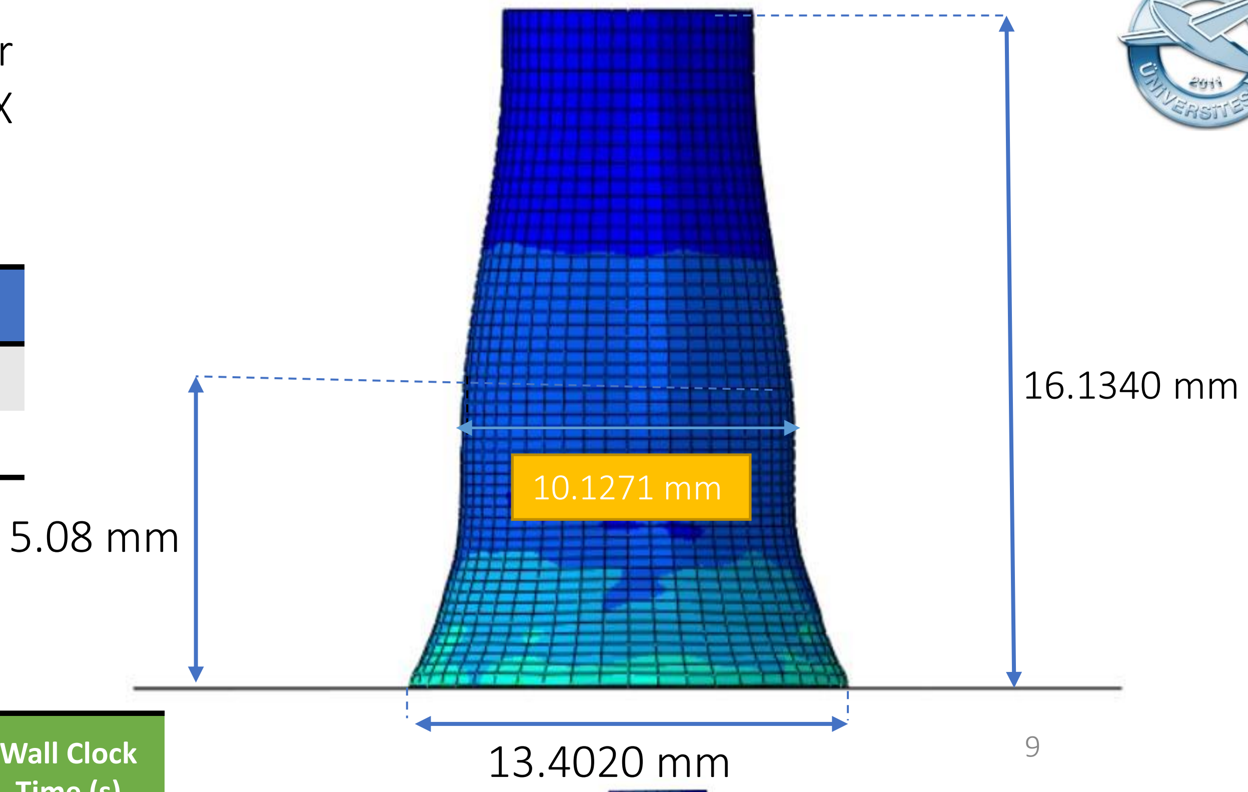
Element Size	0.2				0.3				0.4				0.5			
Mesh Type	CAX4R				CAX4R				CAX4R				CAX4R			
Material Model	Von Mises Elastic, Perfectly Plastic		Johnson-Cook		Von Mises Elastic, Perfectly Plastic		Johnson-Cook		Von Mises Elastic, Perfectly Plastic		Johnson-Cook		Von Mises Elastic, Perfectly Plastic		Johnson-Cook	
Hourglass Control	C*	D*	C*	D*	C*	D*	C*	D*	C*	D*	C*	D*	C*	D*	C*	D*
Analysis No	9	10	25	26	11	12	27	28	13	14	29	30	15	16	31	32
Status	C**	A**	C**	C**	C**	C**	C**	C**	C**	C**	C**	C**	C**	C**	C**	C**
Max Von Mises (MPa)	270.967	-	388.456	470.448	268.451	308.456	380.682	1013.654	268.627	312.201	384.477	1020.038	265.279	314.000	386.465	977.890
U_{1max} (mm)	5.334	-	2.987	2.991	5.369	5.385	2.993	2.995	5.386	5.400	2.974	2.983	5.383	5.420	2.965	2.986
U_{1min} (mm)	-0.001	-	-0.058	-0.054	-0.001	-0.049	-0.101	-0.009	-0.003	-0.002	-0.053	-0.008	-0.002	-0.004	-0.004	-0.013
U_{2max} (mm)	0.630	-	0	0	0.620	0.678	0	0	0.530	0.602	0	0	0.504	0.631	0	0
U_{2min} (mm)	-8.758	-	-9.669	-9.670	-8.756	-8.756	-9.708	-9.708	-8.750	-8.751	-9.734	-9.739	-8.737	-8.738	-9.746	-9.748
U_{3max} (mm)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
U_{3min} (mm)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Average Error	0.1808	-	0.0144	0.0146	0.1794	0.1797	0.0160	0.0161	0.1804	0.1799	0.0161	0.0167	0.1815	0.1820	0.0161	0.0172
Total CPU Time (s)	0,3	-	0,3	0,2	0,2	0,1	0,2	0,1	0,1	0,1	0	0	0,1	0	0,1	0
Wall Clock Time (s)	1	-	0	0	0	0	0	1	0	0	0	0	0	0	0	0



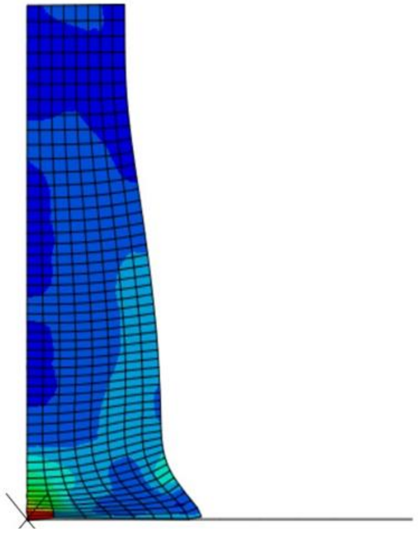
C*:Combined D*:Default A**:The elements contained in element set ErrElemExcessDistortion-Step-1 have distorted excessively. There is only one excessively distorted element. C**:Completed

These values are found coherent with each-other and rather better results are obtained compared to Ma, S. and Zhang, X (2007) using Johnson's expression in terms of average error.

Analysis No	L (mm)	D (mm)	W (mm)	The Average Error ($\bar{\Delta}$)
Experimental Test	16.2	13.5	10.1	-
Analysis #24	16.1340	13.4020	10.1271	0.0047



Analysis	L (mm)	D (mm)	W (mm)	The Average Error ($\bar{\Delta}$)	Total CPU Time (s)	Wall Clock Time (s)
Experimental Test	16.2	13.5	10.1	-	-	-
Analysis #25	15.7310	13.5740	10.1794	0.0144	0.3	0
From Literature (SPH1)	15.4	15.6	9.9	0.075	172	179
From Literature (SPH2)	15.5	14.7	10.0	0.047	204	209
From Literature (MPM)	16.3	13.0	9.6	0.031	78	79



Model Verification

Hawkyard's equation for mushrooming,

$$\frac{\rho_0 v^2}{Y} = 2\left[ln\left(\frac{1}{1-e}\right) - e\right]$$

$$e = 0.7093$$

The deformed diameter, *D*, for copper bar,

$$\frac{A}{A_0} = \frac{1}{1-e}$$

$$r = 6.9833\, mm$$

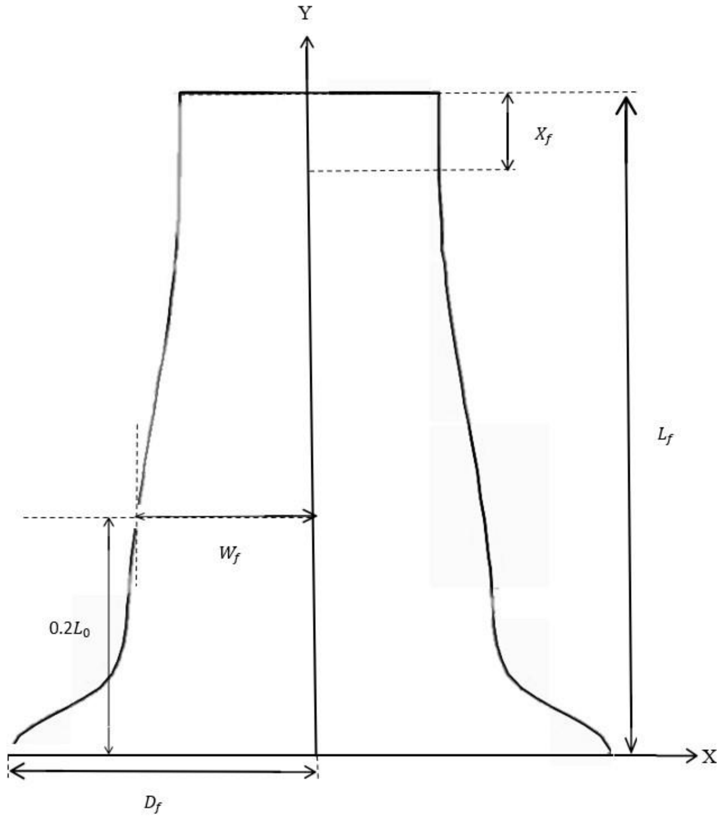
$$\boldsymbol{D \cong 13.97\, mm}$$

The final length of rigid region, x_f,

$$x_f = (1 - e_0)L_0$$

$$\boldsymbol{x_f \cong 7.52\, mm}$$

Dimensions	Test Data	Taylor's Approach	Hawkyard's Approach
D	13.50 mm	12.32 mm	13.97 mm
x_f	-	6.95 mm	7.52 mm



Conclusions

- Hawkyard (1969) adopted the same deformation mode as that proposed by Taylor (1948), but he employed the global energy balance instead of the local momentum balance at the plastic front as used by Taylor (1948).

- Analytical verification using Hawkyard's approach gives reasonable % error regarding deformed diameter for OFHC cylindrical bar. The error is computed ~3.5 % compared to experimental values obtained by Zhang and Ma (2007). However, Taylor's approach possess ~9.5% error accordingly.

- In Hawkyard's approach, the true strain is adopted to replace the engineering strain used in Taylor's approach, which produces a reasonable improvement in large deformation cases.

Thank you for listening