Investigation of Novel Lattice Designs for 3D Printing

Hyunwoo Lee
Mechanincal and Aerospace Enginnering

Associate professor Lai Changquan
Mechaincial and Aerospace Enginnering and Material Science and Enginnering

Dr. Ian Seetoh Peiyuan
Temaset lab at NTU

***Abstract* –** Additive manufacturing technology, with its numerous advantageous, present superior means of lattice construction. A study was conducted to investigate the mechanical properties of novel lattice designs composed of two different type of unit cells. Lattice with no internal voids were studied as to mitigate the limitations of 3D printing not being able to print structures with internal voids. Sixteen different 3x3x3 symmetrical lattice compositions, consisted of truss simple cubic unit cell and plate simple cubic unit cell, was modelled, and simulated using finite element analysis. Variation of relative modulus of the lattice against relative density of the lattice showed consistent patterns despite variation in unit cell thickness. (1mm, 2mm, 3mm, 4mm) Furthermore, pattern revealed that lattice with 19 plate unit cell had the largest relative modulus among lattices with no internal voids. Optimization of unit cell thickness at given relative density has also showed lattice with 19 plate unit cell to have optimal mechanical properties among internal void free lattices. Further optimization on lattice with only 19 plate unit cell and no truss unit cell was done to discover that the specific configuration shows superior mechanical properties in some relative densities. Lattice with 7 plate unit cell, albeit its inferior mechanical properties compared to 19 plate unit cell lattice, showed exceptional properties compared to compositions with similar number of plate unit cell.

Although pure plate simple cubic lattice shows superior mechanical properties, Lattice configuration with 19 plate unit cell is able to substitute pure lattice with minimal loss in mechanical properties while allowing 3D printing due to its internal void free structure.

Keywords – Additive manufacturing, Lattice construction, Finite element analysis

1 INTRODUCTION

1.1 BACKGROUND

3D printing has many advantages compared to conventional manufacturing means, including but not limited to accessibility, faster speed, reduced cost, ease of prototyping, and feasibility of complex geometries. 3D printing technology is being utilized in wide range of fields, including manufacturing, medicine, and construction [1]. However, one main disadvantage of 3D printing is its inability to print geometries with internal voids. This disadvantage influences many different fields, notably lattice construction. Many lattices, due to the unit cell geometries, have internal voids, rendering them infeasible for construction using 3D printing.

1.2 OBJECTIVES

The objective of the study is to investigate in a novel lattice consisted of two different unit cell types to obtain internal void free lattice with mechanical properties similar or superior to that of the pure lattice consisted of one unit cell type. Simulations on different lattice compositions were done to find the optimal configuration that could substitute pure lattices while allowing for 3D printing.

1.3 SCOPE

16 different 3x3x3 symmetrical lattices consisted of plate simple cubic unit cell and truss simple cubic unit cell is investigated using finite element analysis. The effect of unit cell thickness on mechanical properties of lattice is studied and unit cell thickness optimization is carried out to determine the optimal lattice configuration with superior mechanical properties.

2 LITERATURE REVIEW

Literature review was conducted to understand the basics of finite element analysis and different mechanical properties of lattices, such as modulus or relative density.

2.1 FINITE ELEMENT ANALYSIS (FEA)

FEA is a computed method to predict how a model will react to real life phenomenon like heat, force, or magnetism. In involves splitting the model of interest into small meshes to study. For this investigation, stress analysis on a model will be extensively used to evaluate the stress lattice receives with prescribed displacements. COMOSOL Multiphysics will be used for the FEA of the investigation. [2]

2.2 ISOSTRAIN AND ISOSTRESS

Isostrain and isostress are two principles that appear in mechanics of composites. Since the lattice investigated in this study is consisted of two different unit cell types, it can be treated as a composite of two different unit cell types. Isostrain is applicable if the layer of composite is parallel to the direction of stress applied, while isostress is applicable if the layer of composite is perpendicular to the direction of stress applied. The 3x3x3 lattice to be investigated will apply isostrain principle on each of its layers and apply isostress principle to combine the three layers to produce an estimation of mechanical property of composite lattice.

2.3 RULE OF MIXTURES

Rule of mixture states that the property of composites can be approximated by a weighted average of its constituent components. In this investigation, the mechanical property of composite lattice can be approximated using property of its constituent unit cells. Furthermore, it can be predicted that the property of composite lattice must be superior then property of pure unit cell consisted of truss simple cubic unit cell, unit cell of inferior property, and inferior then property of pure unit cell consisted of plate simple cubic unit cell, unit cell of superior property.

3 METHODOLOGY

Methods used to carry out this investigation is outlined in this section. This includes the production of lattice models and finite element analysis studies to investigate mechanical properties of the lattices.

3.1 LATTICE CONSTRUCTION

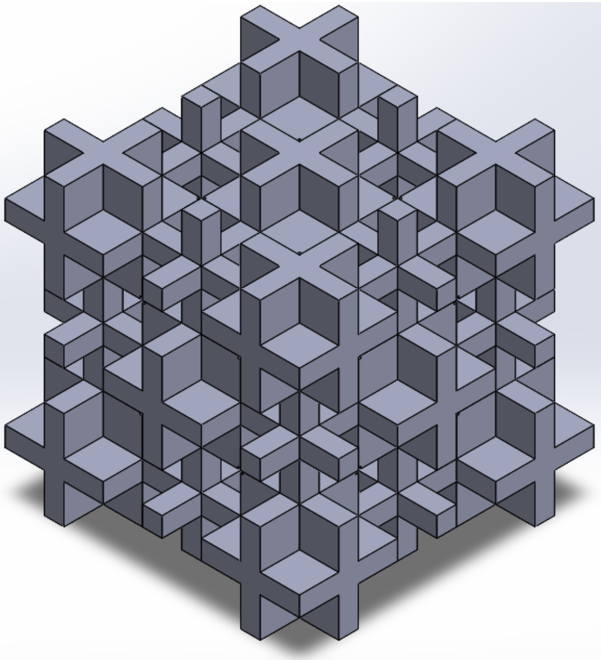

Figure 1: 14 plate unit cell lattice in solid works

Sixteen different 3x3x3 symmetrical lattice consisted of plate simple cubic unit cell and truss simple cubic unit cell were developed using solid works. Each unit cell was 10mm in length, width, and height. The thickness of the unit cells was parameterized for altering purposes and optimization purposes.

3.2 STATIONARY STUDY FOR LATTICE ELASTIC MODULUS

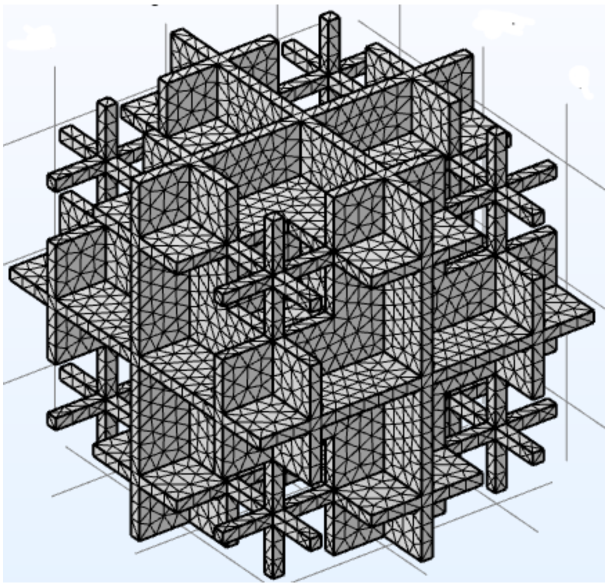

Figure 2: Meshed lattice in COMSOL

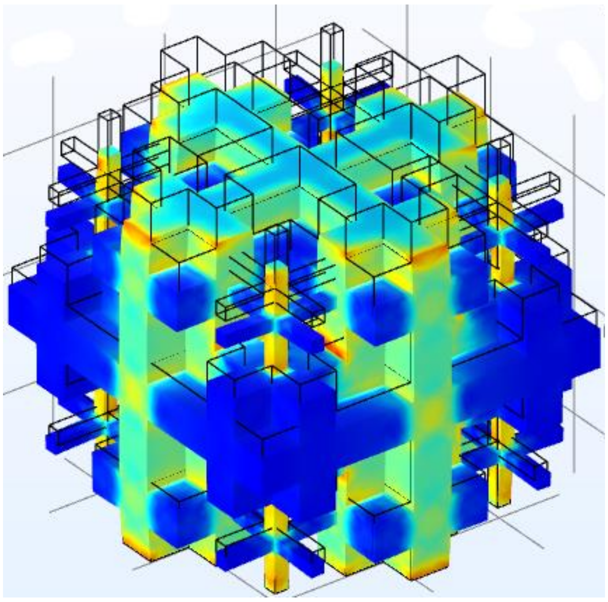

Figure 3: Stress Concentration of Lattice under prescribed displacement in COMSOL

Each lattice configuration was imported into COMSOL to undergo stationary finite element analysis to simulate mechanical stress under effective strain of 0.1% to 1% with 0.1% interval. The stress strain plot was obtained, and the slope of the plot was used as the elastic modulus of the lattice. Unit cell thickness of lattice was varied from 1mm to 4mm with 1mm interval to simulate mechanical stress with equal strain conditions.

3.3 LATTICE UNIT CELL THICKNESS OPTIMIZATION

Each lattice configuration with their unit cell thickness parameterized was imported into COMSOL to undergo thickness optimization to yield optimal stress at a 1 percent strain at given relative densities. Relative density computed range from 0.2 to 0.9, with 0.1 intervals. Configurations that showed exceptional properties were further tested by removing the truss simple cubic unit cell from the lattice, allowing COMSOL to alter only the thickness of plate simple cubic unit cell during the optimization.

4 RESULTS AND DISCUSSIONS

4.1 RESULTS OF STATIONARY STUDY FOR LATTICE ELASTIC MODULUS

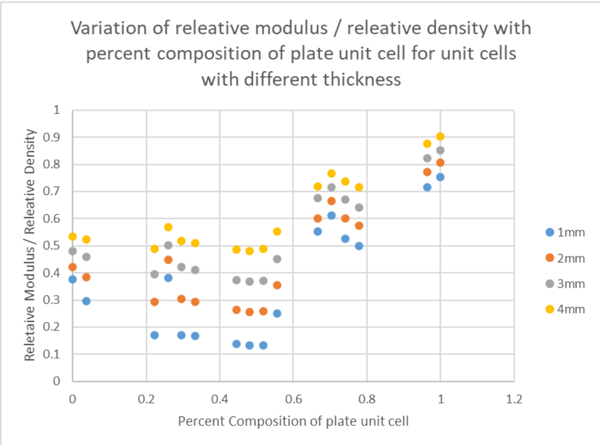

Figure 4: Variation of Specific Relative Modulus for Different Plate Simple Cubic Unit Cell Composition of Lattice with Different Unit Cell Thickness

The table used to generate figure 4 can be found in the appendix. From the results collected from stationary analysis shown in figure 4, variation trend of specific relative modulus shows consistency, regardless of different unit cell thickness. Furthermore, lattice with plate simple cubic unit cell composition of 25.93 percent and 70.37 percent, or lattice with 7 and 19 plate simple cubic unit cell, showed exceptional properties, as compared to its neighboring points, while not having internal voids in its structures. Since the exceptional property was evident in all unit cell thickness, the two configurations are to be investigated further in optimization studies to verify their properties. Furthermore, studies on mechanical property of lattice with only 7 and 19 plate simple cubic unit cell and no truss simple cubic unit cell will be studied to test if superior properties compared to its original configuration can be achieved.

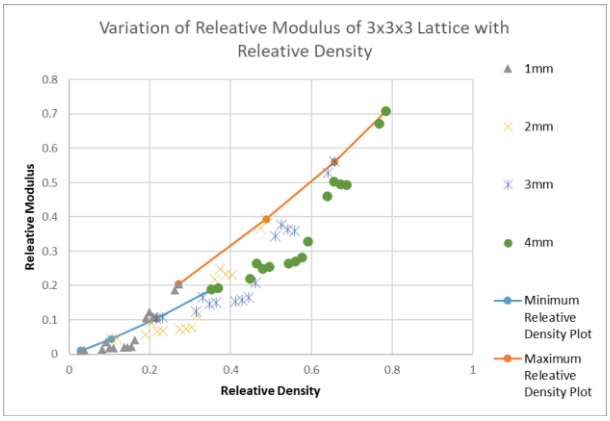

Figure 5: Variation of Relative Modulus of Lattice with Relative Density

Same data used to generate figure 4 was used to generate figure 5, which shows how the relative modulus of lattice varies with relative density of the lattice. The variation trend of specific relative modulus observed in figure 4 is observable in figure 5, with differences in magnitude of relative modulus variation, showing greater changes at higher relative densities. Furthermore, it can be observed that none of the points fall beneath the minimum relative modulus (0 plate simple cubic unit cell lattice) and exceed above the maximum relative modulus (27 plate simple cubic unit cell lattice), proving that the study follows the rule of mixtures.

4.2 RESULTS OF STATIONARY STUDY FOR PURE LATTICES

To compare the mechanical properties of optimized compound lattice, mechanical properties of pure lattices consisted of single unit cell type was obtained.

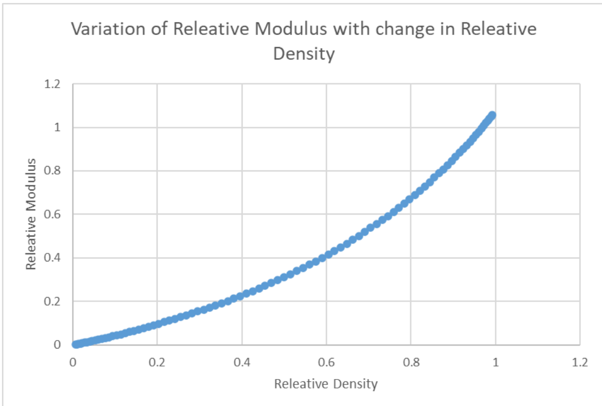

Figure 6: Variation of Relative Modulus of Truss Simple Cubic Lattice with Relative Density

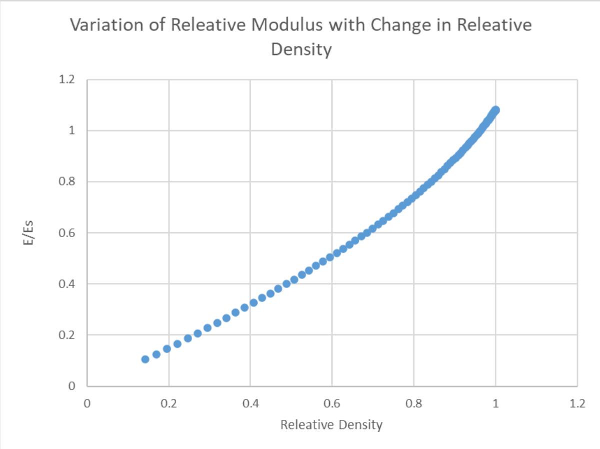

Figure 7: Variation of Relative Modulus of Plate Simple Cubic Lattice with Relative Density

4.3 RESULTS OF LATTICE UNIT CELL THICKNESS OPTIMIZATION

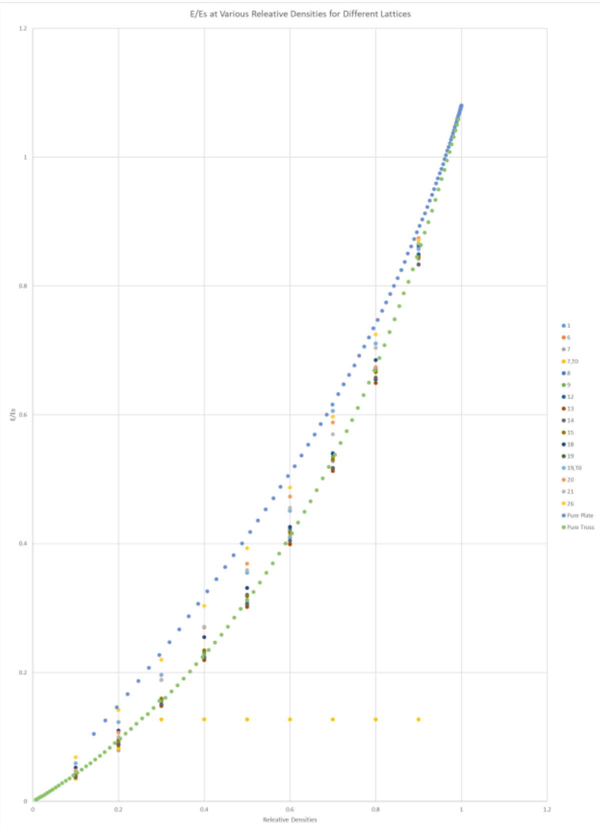

Figure 8: Variation of Optimized Relative Modulus Against Relative Densities of Different Lattice Configuration

With reference to figure 8, lattice with 19 plate simple cubic unit cell showed optimal mechanical properties at almost all relative densities, lattice with only 19 plate simple cubic unit cell showed optimal mechanical properties at other relative densities. It was also observed that at 0.5 and 0.6 relative densities, lattice with 20 plate cubic unit cell showed optimal mechanical properties among all other configurations. Comparing the optimal mechanical properties of a lattice at given relative densities with the mechanical properties of pure plate simple cubic lattice, the composite lattice is able to attain relative modulus that is comparable to that of the pure lattice while having no internal voids in its structures.

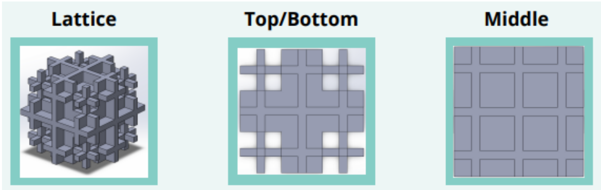

Figure 9: Structure of 19 plate unit cell lattice

6 CONCLUSION

In Conclusion, lattice consisted of 19 plate simple cubic unit cell showed optimal mechanical properties in both stationary study of lattice modulus and unit cell thickness optimization. Furthermore, its relative modulus was comparable to that of the relative modulus of pure plate simple cubic lattice. The lattice configuration does not contain internal voids, making it suitable for construction via 3D printing.

Moreover, lattice consisted of only 19 plate unit cell showed superior properties in certain relative densities, while lattice with 20 plate unit cell showed superior properties in specific relative density regions.

Further studies may be conducted to find the range of relative densities in which specific configuration shows optimal properties. Also, physical model of a lattice may be constructed and tested under loading to verify the simulated results. Finally, lattice consisted of other type of unit cells may be simulated to attain the optimal properties of compound lattice and compared with the properties of lattice configurations investigated in this research.

ACKNOWLEDGMENT

The author would like to express his whole heartedly gratitude towards Associate Professor Lai Changquan for his relentless support and guidance throughout this research. The author would also like to express his sincere appreciation towards Dr.Ian, who has provided extensive support and guidance in progressing through the research.

REFERENCES

[1] MakerBot, "Top 3D Printing Applications Across Industries | MakerBot," *MakerBot*, Apr. 18, 2019. https://www.makerbot.com/stories/design/top-5-3d-printing-applications/ (accessed May 06, 2022).

[2] "Finite Element Analysis Software | Autodesk," *Autodesk.com*, Dec. 04, 2020. https://www.autodesk.com/solutions/finite-element-analysis#:~:text=Finite%20element%20analysis%20(FEA)%20is,the%20way%20it%20was%20designed. (accessed May 06, 2022).

APPENDIX

Table used to generate figure 4:

	1mm	2mm	3mm	4mm
Percent Composition of Plate Unit Cell	Releative Modulus / Releative Density (Specific Releative Modulus)			
0	0.375079431	0.422828089	0.479785728	0.533483988
0.037037037	0.295872873	0.384840055	0.459208643	0.522035024
0.222222222	0.16944777	0.293606594	0.39395387	0.489358315
0.259259259	0.381121101	0.448108773	0.501453383	0.569587905
0.296296296	0.170435657	0.304934416	0.422816434	0.518886785
0.333333333	0.16905347	0.292780042	0.412298467	0.510960411
0.444444444	0.138503565	0.263116578	0.373625331	0.485988933
0.481481481	0.133096482	0.256151259	0.3677156	0.481780844
0.518518519	0.133176309	0.25772514	0.371838399	0.489741162
0.555555556	0.250188387	0.353679972	0.450400754	0.553961405
0.666666667	0.553203296	0.601690236	0.675097841	0.717601641
0.703703704	0.610706563	0.664153261	0.715476807	0.766935206
0.740740741	0.525434149	0.600706002	0.670290001	0.736369799
0.777777778	0.498743006	0.574252709	0.641620137	0.716376556
0.962962963	0.714830365	0.77260852	0.822779617	0.875181503
1	0.752230422	0.80715226	0.852967729	0.903067151

Table used to generate figure 5:

1mm		2mm		3mm		4mm	
Relative Density	Relative Modulus	Relative Density	Relative Modulus	Relative Density	Relative Modulus	Relative Density	Relative Modulus
0.028	0.010502224	0.104	0.043974121	0.216	0.103633717	0.352	0.187786364
0.037	0.010947296	0.118222222	0.045496646	0.232333333	0.106689475	0.368	0.192108889
0.082	0.013894717	0.189333333	0.055589515	0.314	0.123701515	0.448	0.219232525
0.091	0.03468202	0.203555556	0.09121503	0.330333333	0.165646768	0.464	0.264288788
0.1	0.017043566	0.217777778	0.066407939	0.346666667	0.146576364	0.48	0.249065657
0.109	0.018426828	0.232	0.06792497	0.363	0.149664343	0.496	0.253436364
0.136	0.018836485	0.274666667	0.072269354	0.412	0.153933636	0.544	0.26437798
0.145	0.01929899	0.288888889	0.073999253	0.428333333	0.157504848	0.56	0.269797273
0.154	0.020509152	0.303111111	0.078119354	0.444666667	0.165344141	0.576	0.282090909
0.163	0.040780707	0.317333333	0.112234444	0.461	0.207634747	0.592	0.327945152
0.19	0.105108626	0.36	0.216608485	0.51	0.344299899	0.64	0.459265051
0.199	0.121530606	0.374222222	0.248540909	0.526333333	0.376579293	0.656	0.503109495
0.208	0.109290303	0.388444444	0.233340909	0.542666667	0.36374404	0.672	0.494840505
0.217	0.108227232	0.402666667	0.231232424	0.559	0.358665657	0.688	0.492867071
0.262	0.187285556	0.473777778	0.366044747	0.640666667	0.527127475	0.768	0.672139394
0.271	0.203854444	0.488	0.393890303	0.657	0.560399798	0.784	0.708004646

Table used to generate figure 8:

Mixed Lattice	E/Es																
Releative Densities	1	6	7	7,T0	8	9	12	13	14	15	18	19	19,T0	20	21	26	Mqs
0.1	0.041754	0.039097	0.035294	0.035433	0.041158	0.040689	0.038257	0.037417	0.037986	0.041982	0.052586	0.05904	0.058904	0.048427	0.045408	0.06865	0.06865
0.2	0.094288	0.089683	0.079281	0.081733	0.094283	0.092869	0.088773	0.087217	0.08853	0.095448	0.11013	0.1233	0.123267	0.106701	0.099832	0.141789	0.141789
0.3	0.155067	0.148678	0.158944	0.127333	0.157556	0.155478	0.150533	0.1483	0.1508	0.159978	0.188344	0.196322	0.194056	0.188922	0.188511	0.219944	0.219944
0.4	0.225044	0.219622	0.228567	0.127333	0.232378	0.230289	0.222256	0.219644	0.223211	0.234489	0.255089	0.270311	0.269744	0.270289	0.270967	0.303433	0.303433
0.5	0.309133	0.301489	0.313256	0.127333	0.321078	0.318078	0.306444	0.3025	0.3064	0.319378	0.331444	0.355056	0.355656	0.3689	0.359089	0.392956	0.392956
0.6	0.408644	0.398856	0.411922	0.127333	0.422511	0.418878	0.404433	0.399544	0.403856	0.417289	0.425922	0.451378	0.459811	0.473189	0.456033	0.4875	0.4875
0.7	0.528578	0.515011	0.528211	0.127333	0.540689	0.5344	0.517844	0.5129	0.517256	0.530811	0.539867	0.606033	0.6065	0.588333	0.569767	0.597244	0.6065
0.8	0.669533	0.655522	0.671478	0.127333	0.672556	0.6681	0.6547	0.649511	0.657956	0.666311	0.685233	0.7106	0.614656	0.674011	0.703711	0.724722	0.724722
0.9	0.848456	0.846511	0.842144	0.127333	0.861178	0.865167	0.849322	0.833456	0.833233	0.844867	0.864589	0.857411	0.614656	0.874311	0.865978	0.870678	0.874311

Table used to generate figure 6:

Truss Thickness	Releative Density	Reaction Force	E/Es
0.5	0.00725	2.3238	0.002582
0.6	0.010368	3.3713	0.003745889
0.7	0.014014	4.6073	0.005119222
0.8	0.018176	6.0712	0.006745778
0.9	0.022842	7.7281	0.008586778
1	0.028	9.5742	0.010638
1.1	0.033638	11.752	0.013057778
1.2	0.039744	14.044	0.015604444
1.3	0.046306	16.518	0.018353333
1.4	0.053312	19.313	0.021458889
1.5	0.06075	22.269	0.024743333
1.6	0.068608	25.392	0.028213333
1.7	0.076874	28.779	0.031976667
1.8	0.085536	32.345	0.035938889
1.9	0.094582	36.177	0.040196667
2	0.104	40.184	0.044648889
2.1	0.11378	44.412	0.049346667
2.2	0.1239	48.905	0.054338889
2.3	0.13437	53.518	0.059464444
2.4	0.14515	58.38	0.064866667
2.5	0.15625	63.524	0.070582222
2.6	0.16765	68.877	0.07653
2.7	0.17933	74.94	0.083266667
2.8	0.1913	81.545	0.090605556
2.9	0.20352	87.937	0.097707778
3	0.216	94.642	0.105157778
3.1	0.22872	101.25	0.1125
3.2	0.24166	108.56	0.120622222
3.3	0.25483	115.76	0.128622222
3.4	0.26819	122.25	0.135833333
3.5	0.28175	130.55	0.145055556
3.6	0.29549	140.6	0.156222222
3.7	0.30939	144.84	0.160933333
3.8	0.32346	153.57	0.170633333
3.9	0.33766	162.24	0.180266667
4	0.352	171.75	0.190833333
4.1	0.36646	181.61	0.201788889
4.2	0.38102	191.7	0.213
4.3	0.39569	201.65	0.224055556
4.4	0.41043	211.64	0.235155556
4.5	0.42525	221.99	0.246655556
4.6	0.44013	232.68	0.258533333
4.7	0.45505	244.11	0.271233333
4.8	0.47002	256.65	0.285166667
4.9	0.485	268.98	0.298866667
5	0.5	281.5	0.312777778
5.1	0.515	292.64	0.325155556
5.2	0.52998	305.99	0.339988889
5.3	0.54495	319.32	0.3548
5.4	0.55987	332.68	0.369644444
5.5	0.57475	346.16	0.384622222
5.6	0.58957	360.27	0.4003
5.7	0.60431	374.76	0.4164
5.8	0.61898	389.47	0.432744444
5.9	0.63354	404.7	0.449666667
6	0.648	419.43	0.466033333
6.1	0.66234	434.71	0.483011111
6.2	0.67654	451.16	0.501288889
6.3	0.69061	467.42	0.519355556
6.4	0.70451	484.1	0.537888889
6.5	0.71825	500.9	0.556555556
6.6	0.73181	517.35	0.574833333
6.7	0.74517	533	0.592222222
6.8	0.75834	549.74	0.610822222
6.9	0.77128	567.38	0.630422222
7	0.784	584.88	0.649866667
7.1	0.79648	601.92	0.6688
7.2	0.8087	619.57	0.688411111
7.3	0.82067	637.43	0.708255556
7.4	0.83235	655.61	0.728455556
7.5	0.84375	673.68	0.748533333
7.6	0.85485	692.09	0.768988889
7.7	0.86563	709.65	0.7885
7.8	0.8761	726.02	0.806688889
7.9	0.88622	743.11	0.825677778
8	0.896	760.91	0.845455556
8.1	0.90542	777.19	0.863544444
8.2	0.91446	794.62	0.882911111
8.3	0.92313	809.4	0.899333333
8.4	0.93139	825.19	0.916877778
8.5	0.93925	840.43	0.933811111
8.6	0.94669	854.68	0.949644444
8.7	0.95369	869.57	0.966188889
8.8	0.96026	881.99	0.979988889
8.9	0.96636	895.33	0.994811111
9	0.972	907.33	1.008144444
9.1	0.97716	918.11	1.020122222
9.2	0.98182	928.48	1.031644444
9.3	0.98599	937.42	1.041577778
9.4	0.98963	945.49	1.050544444
9.5	0.99275	952.68	1.058533333

Table used to generate figure 7:

Plate Thickness	Releative Density	Reaction Force	E/Es
0.5	0.14262	94.368	0.104853333
0.6	0.16942	113.01	0.125566667
0.7	0.19564	131.56	0.146177778
0.8	0.22131	149.95	0.166611111
0.9	0.24643	168.28	0.186977778
1	0.271	186.49	0.207211111
1.1	0.29503	204.75	0.2275
1.2	0.31853	222.58	0.247311111
1.3	0.3415	240.54	0.267266667
1.4	0.36394	258.55	0.287277778
1.5	0.38588	276.3	0.307
1.6	0.4073	293.5	0.326111111
1.7	0.42821	310.38	0.344866667
1.8	0.44863	327.24	0.3636
1.9	0.46856	343.85	0.382055556
2	0.488	360.27	0.4003
2.1	0.50696	376.41	0.418233333
2.2	0.52545	392.33	0.435922222
2.3	0.54347	408.18	0.453533333
2.4	0.56102	423.55	0.470611111
2.5	0.57813	439.41	0.488233333
2.6	0.59478	454.36	0.504844444
2.7	0.61098	468.46	0.520511111
2.8	0.62675	483.53	0.537255556
2.9	0.64209	498.42	0.5538
3	0.657	512.63	0.569588889
3.1	0.67149	527.05	0.585611111
3.2	0.68557	540.46	0.600511111
3.3	0.69924	554.6	0.616222222
3.4	0.7125	568.91	0.632122222
3.5	0.72537	582.66	0.6474
3.6	0.73786	595.77	0.661966667
3.7	0.74995	608.97	0.676633333
3.8	0.76167	622.7	0.691888889
3.9	0.77302	635.48	0.706088889
4	0.784	648.03	0.720033333
4.1	0.79462	660.67	0.734077778
4.2	0.80489	672.86	0.747622222
4.3	0.81481	685.16	0.761288889

4.4	0.82438	696.95	0.774388889
4.5	0.83362	708.83	0.787588889
4.6	0.84254	720.07	0.800077778
4.7	0.85112	731.2	0.812444444
4.8	0.85939	742.34	0.824822222
4.9	0.86735	753.78	0.837533333
5	0.875	765.23	0.850255556
5.1	0.88235	775.49	0.861655556
5.2	0.88941	785.67	0.872966667
5.3	0.89618	795.07	0.883411111
5.4	0.90266	804.14	0.893488889
5.5	0.90888	812.79	0.9031
5.6	0.91482	821.62	0.912911111
5.7	0.92049	830.21	0.922455556
5.8	0.92591	839.25	0.9325
5.9	0.93108	847.48	0.941644444
6	0.936	855.56	0.950622222
6.1	0.94068	863.23	0.959144444
6.2	0.94513	870.62	0.967355556
6.3	0.94935	877.6	0.975111111
6.4	0.95334	883.64	0.981822222
6.5	0.95712	890.16	0.989066667
6.6	0.9607	897.41	0.997122222
6.7	0.96406	903.04	1.003377778
6.8	0.96723	909.16	1.010177778
6.9	0.97021	914.43	1.016033333
7	0.973	919.57	1.021744444
7.1	0.97561	924.44	1.027155556
7.2	0.97805	928.99	1.032211111
7.3	0.98032	933.34	1.037044444
7.4	0.98242	937.31	1.041455556
7.5	0.98437	941.43	1.046033333
7.6	0.98618	944.81	1.049788889
7.7	0.98783	947.97	1.0533
7.8	0.98935	950.93	1.056588889
7.9	0.99074	953.67	1.059633333
8	0.992	956.28	1.062533333
8.1	0.99314	958.56	1.065066667
8.2	0.99417	960.57	1.0673
8.3	0.99509	962.34	1.069266667
8.4	0.9959	963.93	1.071033333
8.5	0.99662	965.47	1.072744444
8.6	0.99726	966.81	1.074233333
8.7	0.9978	967.96	1.075511111
8.8	0.99827	968.76	1.0764
8.9	0.99867	969.68	1.077422222
9	0.999	970.38	1.0782
9.1	0.99927	970.93	1.078811111
9.2	0.99949	971.42	1.079355556
9.3	0.99966	971.78	1.079755556
9.4	0.99978	972.03	1.080033333
9.5	0.99987	972.19	1.080211111