#### 4.0 Depth Analysis – Lateral Force Resisting System 4.1 Existing System – Braced Frames

The existing lateral force resisting system was previously assessed for its load carrying capacity and potential for improvement. As described in Section 2.3, the existing system is composed of ten concentrically braced frames spaced throughout the building. Computer models were created and analyzed using SAP2000 to determine the characteristic stiffness of each frame. This information was dumped into an Excel spreadsheet (Figure 4.1.1) to distribute the seismic base shear to the individual frames according to the equivalent lateral force method as described in ASCE 7-02. The SAP2000 models are not provided in this report.

To further deconstruct the braced frames, I distributed the lateral story forces to the diagonal bracing members using an Excel spreadsheet. The members were checked for allowable compression and tension strengths using the design tools in the *Manual of Steel Construction: Load and Resistance Factored Design (LRFD), 3<sup>rd</sup> Edition* published by the American Institute for Steel Construction (AISC). In addition, total story drift was calculated using design procedures described in *The Seismic Design Handbook, 2<sup>nd</sup> Edition* by Farzad Naeim for undamped Multi-Degree of Freedom (MDOF) systems under static loading. Stiffness matrices (Appendix B) were created from the calculated axial stiffness values of the bracing members. The results of the force distribution, allowable strength comparisons, and total story drifts are available for review in Figure 4.1.2.

Upon review, the existing system was adequate to resist the calculated seismic load. Overall, the capacity of the system is underutilized and presents the opportunity for streamlining, which is described in the next section.

						Overturning	Moment (in-k)	34480	32335	78907	118299	37830	16578	96422	74373	73261	74373				
							Total Shear (k) Moment (in-k)	6'96	6'06	221.8	332.5	106.3	46.6	271.0	209.0	205.9	209.0				
			_			Eccentric	Shear (k)	-5.9	-5.9	4.6	6.1	6.5	-3.0	-0.4	-0.3	-0.3	-0.3				
.c		'n				(kd)	SUM(kd <sup>2</sup> )	0.0002	0.0002	0.0001	0.0003	0.0002	0.0001	0.0000	0.0000	0.0000	0.0000				
168	336	516					k*ď²	290056869	305873351	75595481	157550150	318232574	156822757	6163296	4753942	6267395	6362582				
h,	h <sub>2</sub>	h3			ce Method		k*d	257603	256172	198944	351661	282626	131341	36926	28483	32458	32951				
		L	1		it Lateral Ford		(iii) p	1126	1194	380	448	1126	1194	167	167	193	193				
0.230	0.444	0.325			Shear Distribution by Equivalent Lateral Force Method	Direct Shear	(k)	96'9	90.9	221.8	332.5	106.3	46.6	271.0	209.0	205.9	209.0				
C <sub>81</sub>	C <sub>82</sub>	C <sub>83</sub>			Distribution	% Direct	Load	10.83%	10.15%	24.78%	37.15%	11.88%	521%	30.28%	23.36%	23.01%	23.36%				
			1		Shear	×	(k/in)	228.78	214.55	523.56	784.93	251.00	110.00	22124	170.65	168.10	170.65				
	$M = V^* e_x$	$M = V^{e_y}$				in/kip	(STAAD)	0.00437	0.00466	0.00191	0.00127	0.00398	60600.0	0.00452	0.00586	0.00595	0.00586				
×	in-k	÷	n	•		y-coord.	(in.)		,		,			480	480	840	840	647	662	-15	
895	-30445	-13508	1.29			x-coord.	(in.)	380	2700	1126	1954	380	2700					1506	1540	-34	
Base Shear	Torsion (E-W)	(N-S) r	vift Limit				Direction	E-W	E-W	E-W	E-W	E-W	E-W	s-N	s-v	s-N	S-N	C.O.R.	C.O.M.	e	
Base	Torsion	Torsion (N-S)	H/400 Drift Limit				Frame	-	2	9	7	6	10	e	4	5	8				

Figure 4.1.1 Seismic Base Shear Distribution According to the Equivalent Lateral Force Method

Offlittes         (k)         Force (k)         Strength (k)         Cumptes.           S16.2         22.3         83.4         712.1         557         15.0%           816.2         22.3         83.4         712.1         557         15.0%           550.5         43.1         64.2         480.2         303         212%           640.6         20.9         78.2         558.9         390         20.0%           640.6         20.9         78.2         558.9         390         20.0%           640.6         20.9         78.2         56.6         40.3.2         203         13.1%           550.5         62.5         233.1         480.2         303         76.9%         77%           640.6         712.1         86.1         79.4         403.2         203         31.1%           550.5         62.5         233.1         480.2         303         76.9%         77%           640.6         97.9         61.2         403.2         203         31.3%         75.9%           640.6         97.9         61.2         403.2         203         30.7%         77.9%           717.3         51.1         158.4	HSS Brace	Area	Ē	mber Forces Story Shear	Brace Axial	Allowable	Allowable	Strength	Total Story
816.2         22.3         83.4         712.1         557         15.0%         15.0%           760.5         43.1         64.2         480.2         303         212%         15.0%           640.6         315         28.4         403.2         203         14.0%         212%           640.6         315         28.4         403.2         550.3         20.0%         27.%           640.6         20.9         782         568.9         300         20.%         13.1%           640.7         295.5         233.1         403.2         203         13.1%         27.%           640.6         62.5         170.4         60.2         403.2         203         13.1%           640.7         78.1         403.2         203         21.%         27.%           640.6         48.1         79.4         403.2         203         45.%           640.6         62.9         30.1         40.3         203         45.%           640.6         67.6         403.2         203         21.%         27.%           640.6         67.6         403.2         203         21.%         27.%           717.3         51.6	(ui)	(in <sup>2</sup> ) cos(theta)	S	(k)		. (X)	Compress. Strength (k)	Design Efficiency	Drift (in)
550.5         43.1         64.2         480.2         303         212%           401.7         31.5         28.4         403.2         203         14.0%           640.6         20.9         78.2         558.9         390         20.0%         1           462.2         40.4         60.2         403.2         558.9         390         20.0%         1           462.2         40.4         60.2         403.2         203         13.1%         27%         1           462.2         10.4         60.2         403.2         203         13.1%         1         27%         1         27%         1         27%         1         27%         27%         1         27%         27%         1         27%         27%         1         27%         27%         1         27%         27%         1         27%         27%         1         27%         27%         1         27%         27%         1         27%         27%         27%         27%         27%         27%         27%         27%         27%         27%         27%         27%         27%         27%         27%         27%         27%         27%         27% <t< td=""><td>10×10×<sup>1</sup>/<sub>2</sub> 206</td><td>17.2 0.58</td><td></td><td>22.3</td><td></td><td></td><td>557</td><td>15.0%</td><td>0.12</td></t<>	10×10× <sup>1</sup> / <sub>2</sub> 206	17.2 0.58		22.3			557	15.0%	0.12
401.7 $31.5$ $28.4$ $403.2$ $203$ $140%$ $140%$ $640.6$ $20.9$ $78.2$ $56.9$ $330$ $20.0%$ $13.1%$ $462.2$ $40.4$ $60.2$ $403.2$ $203$ $76.9%$ $27%$ $462.2$ $22.5$ $233.1$ $480.2$ $303$ $76.9%$ $77%$ $462.2$ $12.0.4$ $179.4$ $403.2$ $203$ $76.9%$ $76.9%$ $462.2$ $120.4$ $179.4$ $403.2$ $203$ $76.9%$ $76.9%$ $461.7$ $88.1$ $79.4$ $403.2$ $203$ $76.9%$ $76.9%$ $401.7$ $88.1$ $79.4$ $403.2$ $203$ $46.1%$ $76.9%$ $640.6$ $47.5$ $177.1$ $58.0.5$ $32.0$ $46.1%$ $75.%$ $640.6$ $475.6$ $473.6$ $473.6$ $47.9%$ $71.9%$ $717.3$ $61.17.4$ $480.2$ $203$ $204.%$ $71.9%$	206 1	11.6 0.58		43.1	64.2	480.2	303	21.2%	0.25
640.6 $20.9$ $78.2$ $56.9$ $390$ $20.0\%$ $13.1\%$ 462.2         40.4 $60.2$ 403.2 $217$ $27.7\%$ $13.1\%$ 462.2         62.5 $23.31$ $480.2$ $20.3$ $76.9\%$ $13.1\%$ 461.7 $29.5$ $23.31$ $480.2$ $20.3$ $76.9\%$ $13.1\%$ 462.2 $120.4$ $179.4$ $403.2$ $20.3$ $76.9\%$ $13.1\%$ 461.7 $88.1$ $79.4$ $403.2$ $20.3$ $46.1\%$ $13.1\%$ 640.6 $482$ $179.4$ $403.2$ $203$ $46.1\%$ $15.7\%$ 640.6 $47.5$ $177.1$ $58.0$ $3300$ $45.7\%$ $17.5\%$ 640.6 $47.5$ $177.1$ $56.9$ $3002$ $20.7\%$ $17.9\%$ 640.6 $47.5$ $177.1$ $56.9$ $3002$ $45.4\%$ $17.9\%$ 717.3 $61.7$ $135.4$ $480.2$ $203$ $3036$	216 9.	9.74 0.55(		31.5	28.4	403.2	203	14.0%	0.33
462.2 $40.4$ $60.2$ $40.3.2$ $21.7$ $27.7%$ $401.7$ $29.5$ $26.6$ $40.3.2$ $20.3$ $13.1%$ $401.7$ $29.5$ $25.5$ $25.5$ $23.3.1$ $480.2$ $20.3$ $15.9%$ $550.5$ $62.5$ $179.4$ $403.2$ $20.3$ $76.9%$ $82.7%$ $401.7$ $88.1$ $79.4$ $403.2$ $203$ $82.7%$ $82.7%$ $640.6$ $482$ $179.4$ $403.2$ $203$ $45.7%$ $82.7%$ $640.6$ $475$ $177.4$ $480.2$ $203$ $45.7%$ $82.7%$ $401.7$ $67.9$ $61.2$ $403.2$ $203$ $45.7%$ $47.9%$ $717.3$ $98.6$ $61.2$ $403.2$ $203$ $45.7%$ $47.9%$ $717.3$ $98.6$ $60.2$ $403.2$ $203$ $45.7%$ $57.9%$ $717.3$ $98.6$ $712.4$ $480.2$ $245$ $57.9%$	206 13.5			20.9	78.2	558.9	390	20.0%	0.14
401.7 $29.5$ $26.6$ $403.2$ $203$ $13.1%$ $13.1%$ $650.5$ $62.5$ $233.1$ $480.2$ $303$ $76.9%$ $82.7%$ $462.2$ $120.4$ $179.4$ $403.2$ $203$ $361.%$ $82.7%$ $401.7$ $88.1$ $79.4$ $403.2$ $203$ $361.%$ $82.7%$ $401.7$ $88.1$ $79.4$ $403.2$ $203$ $361.%$ $82.7%$ $640.6$ $47.5$ $177.1$ $88.2$ $303.5%$ $367.%$ $87.%$ $401.7$ $67.9$ $612.2$ $403.2$ $203$ $367.%$ $87.%$ $401.7$ $67.9$ $612.7$ $403.2$ $203$ $302.%$ $31.%$ $717.3$ $98.6$ $117.4$ $480.2$ $203$ $32.%$ $32.%$ $32.%$ $717.3$ $98.6$ $712.3$ $403.2$ $203$ $32.%$ $32.%$ $32.%$ $717.3$ $98.6$ $712.3$ <	206 9.74			40.4	60.2	403.2	217	27.7%	0.29
560.5         62.5         233.1         480.2         303         76.9%           462.2         120.4         179.4         403.2         217         82.7%           462.2         120.4         179.4         403.2         203         39.1%           401.7         88.1         79.4         403.2         203         39.1%           640.6         48.2         177.1         558.9         390         46.1%           550.5         92.9         138.4         403.2         203         32%           401.7         67.9         61.2         403.2         203         35.7%           401.7         66.9         60.3         403.2         203         35.7%           401.7         66.9         60.3         403.2         203         35.7%           717.3         51.1         155.6         480.2         236         62.3%           717.3         51.1         155.6         480.2         245         71.9%           717.3         51.1         155.6         480.2         245         71.9%           717.3         147.8         176.0         245         71.9%         71.9%           717.3         1	216 9.74	_	_	29.5	26.6	403.2	203	13.1%	0.37
462.2         120.4         179.4         403.2         217         82.7%           401.7         88.1         79.4         403.2         203         39.1%           401.7         88.1         79.4         403.2         203         39.1%           550.5         92.9         138.4         480.2         30.3         45.7%           550.6         92.9         138.4         480.2         30.3         45.7%           401.7         67.9         61.2         403.2         203         45.4%           401.7         67.9         61.2         403.2         203         45.4%           462.2         91.5         177.1         558.9         30.0         45.4%           401.7         66.9         60.3         403.2         203         45.4%           717.3         91.6         117.4         480.2         217         31.8%           717.3         91.6         177.4         480.2         245         47.9%           717.3         91.6         77.1         31.7         76.9%         71.9%           717.3         147.8         176.0         480.2         245         47.9%           717.3 <t< td=""><td>206 11.6</td><td></td><td></td><td>62.5</td><td>233.1</td><td>480.2</td><td>303</td><td>76.9%</td><td>0.49</td></t<>	206 11.6			62.5	233.1	480.2	303	76.9%	0.49
401.7 $88.1$ $79.4$ $403.2$ $203$ $39.1%$ $640.6$ $482$ $179.8$ $558.9$ $390$ $46.1%$ $550.5$ $92.9$ $138.4$ $480.2$ $330$ $45.7%$ $401.7$ $67.9$ $61.2$ $403.2$ $203$ $45.7%$ $401.7$ $67.9$ $61.2$ $403.2$ $203$ $45.7%$ $401.7$ $65.9$ $61.2$ $403.2$ $203$ $45.7%$ $401.7$ $65.9$ $61.2$ $403.2$ $203$ $45.4%$ $401.7$ $65.9$ $60.3$ $403.2$ $217$ $62.8%$ $717.3$ $90.6$ $117.4$ $480.2$ $245$ $47.9%$ $717.3$ $90.6$ $177.4$ $480.2$ $245$ $47.9%$ $717.3$ $90.6$ $177.4$ $480.2$ $245$ $71.9%$ $717.3$ $90.6$ $71.7$ $80.2$ $71.9%$ $71.9%$ $717.3$ $147.6$	206 9.74			120.4	179.4	403.2	217	82.7%	0.94
640.6         48.2         179.8         558.9         390         46.1%           550.5         92.9         138.4         480.2         303         45.7%           401.7         67.9         61.2         403.2         303         45.7%           401.7         67.9         61.2         403.2         203         302%           401.7         65.9         61.2         403.2         203         35.7%           402.2         91.5         170.3         51.1         558.9         390         45.4%           462.2         91.5         170.3         403.2         203         29.7%         59.7%           717.3         51.1         155.6         480.2         203         29.7%         59.7%           717.3         56.6         72.1         51.3         403.2         203         47.9%           717.3         98.6         117.4         480.2         245         47.9%         59.4%           717.3         76.6         80.2         245         47.9%         56.9%           717.3         76.6         80.2         245         71.9%         71.9%           717.3         76.6         80.2         2	216 9.74		_	88.1	79.4	403.2	203	39.1%	1.16
550.5 $92.9$ $138.4$ $480.2$ $303$ $45.7%$ $45.7%$ $401.7$ $67.9$ $61.2$ $403.2$ $203$ $35.%$ $57.%$ $401.7$ $67.9$ $61.2$ $403.2$ $203$ $302%$ $57.%$ $402.2$ $91.5$ $177.1$ $558.9$ $390$ $45.4%$ $57.%$ $401.7$ $66.9$ $60.3$ $403.2$ $2017$ $62.8%$ $57.%$ $401.7$ $66.9$ $60.3$ $403.2$ $203$ $29.7%$ $77.9%$ $717.3$ $98.6$ $117.4$ $480.2$ $245$ $47.9%$ $77.9%$ $717.3$ $76.6$ $71.3$ $403.2$ $245$ $62.3%$ $71.9%$ $717.3$ $76.6$ $71.3$ $403.2$ $245$ $97.9%$ $71.9%$ $717.3$ $76.6$ $72.1$ $480.2$ $245$ $93.4%$ $71.9%$ $717.3$ $147.8$ $176.0$ $480.2$ $245$ $93.4%$ $71.9%$ $717.3$ $147.8$ $177.0$ $480.2$ $245$ $71.9%$ $71.9%$ $717.3$ $147.8$ $177.0$ $480.2$ $245$ $71.9%$ $71.9%$ $717.3$ $147.8$ $177.0$ $480.2$ $245$ $71.9%$ $71.9%$ $717.3$ $147.8$ $712.1$ $245$ $93.4%$ $71.9%$ $717.3$ $712.1$ $140.2$ $245$ $71.9%$ $71.9%$ $717.3$ $640.2$ $245$ $71.9%$ $71.9%$ $71.9%$ $70.4$ $610.7$ $245$ $93.4%$ $71.9%$ <td< td=""><td>206 13.5</td><td></td><td></td><td>48.2</td><td>179.8</td><td>558.9</td><td>390</td><td>46.1%</td><td>0.33</td></td<>	206 13.5			48.2	179.8	558.9	390	46.1%	0.33
401.7 $67.9$ $61.2$ $403.2$ $203$ $302%$ $54.%$ $640.6$ $47.5$ $177.1$ $558.9$ $390$ $45.4%$ $54.%$ $462.2$ $91.5$ $136.3$ $403.2$ $217$ $62.8%$ $59.7%$ $462.2$ $91.5$ $136.3$ $403.2$ $203$ $29.7%$ $57.%$ $401.7$ $66.9$ $60.3$ $403.2$ $203$ $29.7%$ $57.%$ $717.3$ $51.1$ $152.6$ $480.2$ $245$ $62.3%$ $71.9%$ $717.3$ $76.6$ $51.3$ $403.2$ $161$ $31.8%$ $71.9%$ $717.3$ $76.6$ $72.1$ $51.3$ $403.2$ $245$ $71.9%$ $71.9%$ $717.3$ $76.6$ $72.1$ $51.3$ $403.2$ $245$ $71.9%$ $71.9%$ $717.3$ $76.6$ $72.16$ $480.2$ $245$ $71.9%$ $71.9%$ $71.9%$ $717.3$ $76.6$ $72.16$ $480.2$ $245$ $71.9%$ $71.9%$ $71.9%$ $717.3$ $716.6$ $712.1$ $317$ $76.9%$ $71.9%$ $71.9%$ $717.3$ $714.6$ $712.1$ $317$ $76.9%$ $71.9%$ $76.9%$ $717.3$ $716.6$ $712.1$ $245$ $71.9%$ $71.9%$ $71.9%$ $717.3$ $70.4$ $480.2$ $203$ $203$ $46.1%$ $76.9%$ $717.3$ $70.4$ $712.1$ $317$ $76.9%$ $71.9%$ $717.7$ $67.9$ $712.1$ $302.7%$ $71.9%$ $71.9%$ <td< td=""><td>206 11.6</td><td>0.58</td><td></td><td>92.9</td><td>138.4</td><td>480.2</td><td>303</td><td>45.7%</td><td>0.62</td></td<>	206 11.6	0.58		92.9	138.4	480.2	303	45.7%	0.62
640.6         47.5         177.1         558.9         390         45.4%         177.1           462.2         91.5         136.3         403.2         217         62.8%         16           462.2         91.5         136.3         403.2         217         62.8%         17           401.7         66.9         60.3         403.2         245         62.3%         17           717.3         51.1         152.6         480.2         245         62.3%         17           717.3         51.1         152.6         480.2         245         62.3%         17           717.3         51.1         152.6         480.2         245         62.3%         17           717.3         51.6         71.4         480.2         245         93.4%         17           717.3         147.8         176.0         480.2         245         71.9%         17.9%           717.3         147.4         108.1         243.8         712.1         317         76.9%         71.9%           717.3         147.8         176.0         480.2         245         71.9%         71.9%           717.3         540.6         71.9%         712.	216 9.74	0.55		67.9	612	403.2	203	30.2%	0.79
462.2         91.5         136.3         403.2         217         62.8%         60.3         403.2         23.7%         62.8%         60.3         60.3         203.7%         62.8%         62.3%         73.7%         62.8%         73.7%         62.8%         73.7%         73.3		0.58		47.5	177.1	558.9	390	45.4%	0.32
401.7         66.9         60.3         403.2         203         29.%           717.3         51.1         152.6         480.2         245         62.3%           717.3         98.6         117.4         480.2         245         67.9%           717.3         98.6         117.4         480.2         245         67.9%           545.6         72.1         51.3         403.2         161         31.8%           717.3         76.6         228.8         480.2         245         93.4%           717.3         76.6         228.8         480.2         245         93.4%           717.3         716.0         480.2         245         93.4%         71.9%           717.3         716.1         27.1         317         76.9%         71.9%           717.3         716.1         243.8         712.1         317         76.9%           241.4         108.1         243.8         712.1         317         76.9%           640.6         92.9         91.5         403.2         203         45.7%           640.5         92.9         138.4         480.2         203         45.7%           640.5 <td< td=""><td>206 9.74</td><td>0.58</td><td></td><td>91.5</td><td>136.3</td><td>403.2</td><td>217</td><td>62.8%</td><td>0.66</td></td<>	206 9.74	0.58		91.5	136.3	403.2	217	62.8%	0.66
717.3         51.1         152.6         480.2         245         62.3%           717.3         98.6         117.4         480.2         245         62.3%           545.6         72.1         51.3         403.2         161         31.8%           717.3         76.6         228.8         480.2         245         93.4%           717.3         76.6         228.8         480.2         245         71.9%           717.3         147.8         176.0         480.2         245         71.9%           717.3         147.8         176.0         480.2         245         71.9%           241.4         108.1         243.8         480.2         245         71.9%           640.6         48.2         176.0         480.2         300         46.1%           640.7         67.9         61.2         403.2         203         30.2%           462.2         24.5         91.5         403.2         203         30.2%           462.2         24.5         91.5         403.2         203         30.2%           462.2         24.5         91.5         403.2         203         30.2%           462.2	216 9.74	0.55		6.99	60.3	403.2	203	29.7%	0.83
717.3         98.6         117.4         480.2         245         47.9%           545.6         72.1         51.3         403.2         161         31.8%           717.3         76.5         228.8         480.2         245         93.4%           717.3         147.8         176.0         480.2         245         71.9%           717.3         147.8         176.0         480.2         245         71.9%           241.4         108.1         243.8         712.1         317         76.9%           241.4         108.1         243.8         712.1         317         76.9%           640.6         482         179.8         558.9         303         46.1%           550.5         92.9         138.4         480.2         303         45.7%           401.7         67.9         612         403.2         203         30.2%           462.2         24.5         313.6         403.2         217         42.1%           462.2         24.5         303         302.%         42.1%         42.1%           462.2         24.5         403.2         203         32.4%         42.1%           462.2 <t< td=""><td></td><td>0.72</td><td></td><td>51.1</td><td>152.6</td><td>480.2</td><td>245</td><td>62.3%</td><td>0.31</td></t<>		0.72		51.1	152.6	480.2	245	62.3%	0.31
545.6         72.1         51.3         403.2         161         31.8%           717.3         76.6         228.8         480.2         245         93.4%           717.3         147.8         176.0         480.2         245         93.4%           717.3         147.8         176.0         480.2         245         71.9%           241.4         108.1         243.8         712.1         317         76.9%           240.6         48.2         179.8         558.9         300         46.1%           640.6         48.2         179.8         558.9         303         45.7%           640.7         67.9         61.2         403.2         203         46.1%           401.7         67.9         61.2         403.2         203         45.7%           462.2         24.5         91.5         403.2         203         45.7%           462.2         24.5         91.5         403.2         203         45.7%           462.2         24.5         91.5         403.2         203         45.7%           462.2         24.5         91.5         403.2         203         45.7%           462.2         24	248 11.6	0.72		98.6	117.4	480.2	245	47.9%	0.55
717.3         76.6         228.8         480.2         245         93.4%           717.3         147.8         176.0         480.2         245         71.9%           241.4         108.1         243.8         712.1         317         76.9%           241.4         108.1         243.8         712.1         317         76.9%           640.6         48.2         179.8         558.9         390         46.1%           640.7         67.9         138.4         480.2         303         45.7%           640.7         67.9         61.2         403.2         203         45.7%           462.2         24.5         91.5         403.2         203         32.%           462.2         24.5         91.5         403.2         217         32.4%           462.2         24.5         91.5         403.2         217         32.4%           462.2         24.5         91.5         403.2         217         32.4%           462.2         24.5         91.5         403.2         217         32.4%           462.2         24.5         91.5         403.2         217         32.4%           462.2         20.	256 9.74	0.70		72.1	51.3	403.2	161	31.8%	0.68
717.3         147.8         176.0         480.2         245         719%           241.4         108.1         243.8         712.1         317         76.9%           241.4         108.1         243.8         712.1         317         76.9%           640.6         482         179.8         558.9         390         46.1%           550.5         92.9         138.4         480.2         303         45.7%           401.7         67.9         61.2         403.2         203         30.2%           462.2         24.5         91.5         403.2         203         35.4%           462.2         47.3         70.4         403.2         217         32.4%           462.2         10.7         40.3.2         203         15.3%           462.2         20.7         30.8         403.2         217         15.3%           462.2         20.7         30.8         403.2         217         15.3%           462.2         20.7         30.8         403.2         217         15.3%           462.2         20.7         30.8         403.2         217         15.3%           462.2         20.7         30.8	248 11.6	0.72		76.6	228.8	480.2	245	93.4%	0.46
241.4         108.1         243.8         712.1         317         76.9%           640.6         48.2         179.8         558.9         390         46.1%           550.5         92.9         138.4         480.2         303         45.7%           550.5         92.9         138.4         480.2         303         45.7%           401.7         67.9         61.2         403.2         203         30.2%           462.2         24.5         91.5         403.2         217         42.1%           462.2         47.3         70.4         403.2         217         32.4%           462.2         47.3         70.4         403.2         217         15.3%           462.2         10.7         40.1         403.2         217         15.3%           462.2         20.7         30.8         403.2         217         15.3%           461.7         15.1         13.7         403.2         217         15.3%           461.7         15.1         13.7         403.2         217         14.2%	248 11.6	0.72		147.8	176.0	480.2	245	71.9%	0.82
640.6         48.2         179.8         558.9         390         46.1%           550.5         92.9         138.4         480.2         303         45.7%           401.7         67.9         512.4         480.2         303         45.7%           401.7         67.9         512.4         403.2         203         30.2%           462.2         24.5         91.5         403.2         217         42.1%           462.2         47.3         70.4         403.2         217         32.4%           461.7         34.6         31.2         403.2         203         15.3%           461.7         34.6         31.2         403.2         203         15.3%           462.2         20.7         30.8         403.2         217         18.5%           462.2         20.7         30.8         403.2         217         14.2%           461.7         15.1         13.7         403.2         217         14.2%	406 17.2	0.44		108.1	243.8	712.1	317	76.9%	1.27
550.5         92.9         138.4         480.2         303         45.7%           401.7         67.9         61.2         403.2         203         30.2%           462.2         24.5         91.5         403.2         203         30.2%           462.2         24.5         91.5         403.2         217         42.1%           462.2         34.6         31.2         403.2         217         32.4%           462.2         10.7         34.6         31.2         403.2         203         15.3%           462.2         10.7         40.1         403.2         203         15.3%         403.2         217         18.5%           462.2         20.7         30.8         403.2         217         18.5%         403.2         217         14.2%           461.7         15.1         13.7         403.2         203         6.7%         5.7%		0.58		48.2	179.8	558.9	390	46.1%	0.33
401.7         67.9         61.2         403.2         203         30.2%           462.2         24.5         91.5         403.2         217         42.1%           462.2         47.3         70.4         403.2         217         42.1%           462.2         47.3         70.4         403.2         217         32.4%           401.7         34.6         31.2         403.2         203         15.3%           462.2         10.7         40.1         403.2         217         18.5%           462.2         20.7         30.8         403.2         217         18.5%           462.2         20.7         30.8         403.2         217         14.2%           401.7         15.1         13.7         403.2         203         6.7%	206 11.6	0.58		92.9	138.4	480.2	303	45.7%	0.62
462.2         24.5         91.5         403.2         217         42.1%           462.2         47.3         70.4         403.2         217         32.4%           462.2         47.3         70.4         403.2         217         32.4%           401.7         34.6         31.2         403.2         203         15.3%           462.2         10.7         40.1         403.2         217         18.5%           462.2         20.7         30.8         403.2         217         18.5%           461.7         15.1         13.7         403.2         203         6.7%	216 9.74	0.55	_	67.9	612	403.2	203	30.2%	0.79
462.2         47.3         70.4         403.2         217         32.4%           401.7         34.6         31.2         403.2         217         32.4%           401.7         34.6         31.2         403.2         203         15.3%           462.2         10.7         40.1         403.2         217         18.5%           462.2         20.7         30.8         403.2         217         14.2%           401.7         15.1         13.7         403.2         203         6.7%	206 9.74	0.58		24.5	91.5	403.2	217	42.1%	0.23
401.7         34.6         31.2         403.2         203         15.3%           462.2         10.7         40.1         403.2         203         15.3%           462.2         20.7         30.8         403.2         217         18.5%           462.2         20.7         30.8         403.2         217         14.2%           401.7         15.1         13.7         403.2         203         6.7%	206 9.74	0.58		47.3	70.4	403.2	217	32.4%	0.41
462.2         10.7         40.1         403.2         217         18.5%           462.2         20.7         30.8         403.2         217         14.2%           401.7         15.1         13.7         403.2         203         6.7%	216 9.74	0.55		34.6	31.2	403.2	203	15.3%	0.49
462.2         20.7         30.8         403.2         217         14.2%           401.7         15.1         13.7         403.2         203         6.7%	$\square$	0.58	$\square$	10.7	40.1	403.2	217	18.5%	0.10
401.7 15.1 13.7 403.2 203 6.7%	206 9.74			20.7	30.8	403.2	217	14.2%	0.18
	216 9.74	2010		15.1	13.7	403.2	203	6.7%	0.22

Figure 4.1.2 Diagonal Brace Member Force Distribution, Strength Design Efficiency, and Total Story Drift

#### 4.2 Updated System – Less Frames

The review of the existing lateral force resisting system manifested the opportunity to streamline the existing system and create a new system with a more efficient use of member capacities and total drift limits. I adjusted the Excel spreadsheets from Figure 4.1.1 and Figure 4.1.2 through trial and error to find the best combination of frames and diagonal member sizes. Allowable member strengths were cut-off at 85% to provide some liberty for connection design. The resulting spreadsheets are shown in Figure 4.2.1 and Figure 4.2.2, while the new stiffness matrices are found in Appendix B.

The revised system involves the removal of four braced frames (Frames 4, 5, 9, and 10) and the alteration of three of the remaining frames (Frames 3, 7, and 8). The new frames were remodeled in SAP2000 to determine the new characteristic stiffness. The reduction in the number of frames placed additional seismic loads on the remaining frames' foundations, but the existing spread footings have enough additional capacity to handle the increased loads satisfactorily.

									_	-	_			<u> </u>						
						Overturning	Moment (in-k)	47142	43759	100059	148364		172914			145516				
						Total Shear	(k)	132.5	123.0	281.2	417.0		486.0			409.0				
			_			Eccentric	Shear (k)	15.6	13.4	13.7	16.0		-0.8			-0.8				
i	.u	.c				(kd)	SUM(kd <sup>2</sup> )	0.0003	0.0003	0.0003	0.0003		0.0001			0.0001				
168	336	516					k*ď²	336256017	263227738	113861571	1 02 66 55 69		7342499			8724945				
ĥ,	h2	h <sub>3</sub>			ce Method		k*d	277361	237644	244159	283875		44632			44632				
			1		nt Lateral For		d (in)	1212	1108	466	362		165			195				
0.230	0.444	0.325			Shear Distribution by Equivalent Lateral Force Method	Direct Shear	(k)	116.9	109.6	267.5	401.0		486,0			409.0				
C <sup>el</sup>	C <sub>42</sub>	လိ			r Distributior	% Direct	Load	13.06%	12.25%	29.89%	44.81%		54.30%			45.70%				
				1	Shea	×	(k/in)	228.78	214.55	523.56	784.93		271.30			228.31				
	$M = V^* e_x$	$M = V^{e_y}$				in/kip	(SAP2000)	0.00437	0.00466	0.00191	0.00127		0.00369			0.00438				
×	¥	¥	'n				y-coord. (in.)		,		1		480			840	645	662	-17	
895	16847	-15651	1.29			x-coord.	(in.)	380	2700	1126	1954						1592	1540	52	
Base Shear	Torsion (E-W)	Torsion (N-S)	hift Limit				Direction	E-W	E-W	E-W	E-W		s-N			S-N	C.O.R.	C.O.M.	e	
Base	Torsion	Torsio	H/400 Drift Limit				Frame	Ļ	2	9	7	9 10	9	4	5	8				
	<u></u>		ה		.:1		+:-		1			1:	to	+h	_				.1.	

Figure 4.2.1 Seismic Base Shear Distribution According to the Equivalent Lateral Force Method

Figure 4.2.2 Diagonal Brace Member Force Distribution, Strength Design Efficiency, and Total Story Drift

# 5.0 Depth Analysis – Foundations

### 5.1 Existing System – Spread Footings

The existing foundations are comprised of numerous shallow, spread footings in a system recommended by the geotechnical engineer of record. Designed with a maximum soil bearing capacity of 3000 pounds per square foot (psf), the majority of the footings are 7'x7' to 9'x9'. However, the column footings range in size from the smallest, 4'x4'x1', to the largest combined footing, 17'x38'x4'. That largest footing requires more than 105 cubic yards of concrete!

The largest cast-in-place (CIP) footings support the lateral force resisting braced frames. The column footing schedule for the braced frames is tabulated below in Figure 5.1.1. After improving the braced frame system, I thought it would be rational to assess the foundation system's potential for improvement.

		Dimensions		Botton	n Steel	Тор	Steel	
Frame	Width	Length	Depth	Short Bars	Long Bars	Short Bars	Long Bars	
1	17	38	4	(38) #9	(18) #9	(38) #9	(18) #9	COMBINED FTG
2	17	38	4	(38) #9	(18) #9	(38) #9	(18) #9	COMBINED FTG
3	14	14	3	(13) #8	(13) #8	(13) #8	(13) #8	
4	16	38	3	(38) #9	(16) #9	(38) #9	(16) #9	COMBINED FTG
5	16	38	3	(38) #9	(16) #9	(38) #9	(16) #9	COMBINED FTG
6	16	16	3	(14) #9	(14) #9	(14) #9	(14) #9	
7	16	16	3	(14) #9	(14) #9	(14) #9	(14) #9	
8	16	38	3	(38) #9	(16) #9	(38) #9	(16) #9	COMBINED FTG
9	14	14	3	(13) #8	(13) #8	(13) #8	(13) #8	
10	16	38	3	(38) #9	(16) #9	(38) #9	(16) #9	COMBINED FTG

Figure 5.1.1 Braced Frame Column Footing Schedule

### 5.2 Alternative System - Drilled Concrete Piers

In searching for an alternative foundation system, I re-examined the Geotechnical Investigation Report from the geotechnical engineer of record, Advanced Geoservices Corporation (AGC) of West Chester, Pennsylvania. During the investigation, six test borings were drilled and analyzed to approximate the soil conditions of the building site. Intact rock was encountered in all six borings at depths ranging from 3 feet in the center of the building footprint to 23.5 feet in the southeast corner of the main structure. The rock is described as medium hard gray limestone with graphitic shale laminations and earned a Rock Quality Designation (RQD) of 55%, indicating that the rock is sound with numerous fractures/joints. Using straight-line interpolation between the test borings, I created an approximate three-dimensional rock contour map with the lowest floor elevations intersecting the limestone where rock excavation will be necessary. A plan view of this map is depicted in Figure 5.2.1. An additional three-dimensional perspective view and the original contour map provided by AGC can be found in Appendix B. The threedimensional views helped to approximate the rock depth below the lowest floor elevations for the analysis of an alternative foundation system. Based on the gathered information, I decided that a system of drilled concrete piers extending into the rock base should prove to be an attractive alternative to the CIP spread footings. The project's lead structural engineer, Frank Lancaster of EYP, also suggested a concrete caisson system as the best option to replace the spread footings.

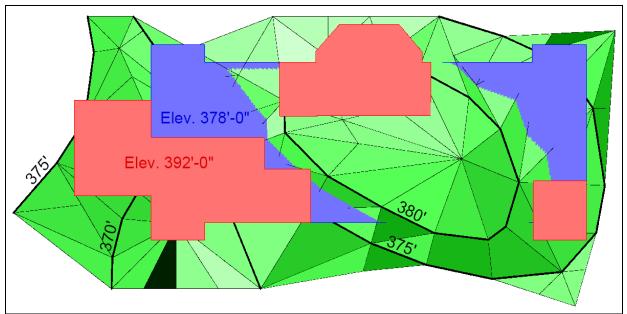


Figure 5.2.1 AutoCAD Approximation of Intact Rock Depth

Given that the footing were largest under the braced frames, these foundations were individually re-designed as drilled piers to assess the overall potential of a new foundation system. All other piers were designed for an anticipated column load of 250 kilo-pounds. To design the new system, I employed a step-by-step procedure to estimate the ultimate bearing capacity of drilled shafts extending into rock from *Principles of Foundation Engineering*, *5<sup>th</sup> Edition* by Braja M. Das, which is available for review in Appendix B.

Unfortunately, the geotechnical report did not include estimated values for the Young's Modulus or the unconfined compression capacity of the local rock. It proved to be very difficult piece of information to garner from libraries or the internet, but I eventually found three sets of limestone strength properties in some very interesting sources. The sources for the information are a technical note entitled "Evaluation of Mechanical Rock Properties" from the *International Journal of Rock Mechanics and Mining Science* and a report entitled "Strength and Deformation Properties of Granite, Basalt, Limestone and Tuff at Various Loading Rates" published by the U.S. Army Corps of Engineers in 1969. The found properties are displayed in the Figure 5.2.2 below.

Rock Description	Young's Modulus (psi)	Unconfined Compression Capacity (psi)
Cordoba Limestone	1.6 x 10 <sup>6</sup>	4600
Indiana Limestone	3.8 x 10 <sup>6</sup>	9000
Light Oilve-Gray, Dense, Very Fine Grained w/ Some Stylolite Seams	11.23 x 10 <sup>6</sup>	11180

Figure 5.2.2 Found Strength Properties of Limestone

Due to the unknown nature of the limestone encountered on the site, the most conservative values were used to design the drilled pier system for the Barshinger Life Science and Philosophy Building. The design calculations were organized and computed in an Excel spreadsheet (Figure 5.2.3). In an attempt to maintain constructability, shaft diameters were limited to one-foot incremental sizes and the shaft depths into rock were restricted to five-foot increments.

											Allowable	Capacity, Q <sub>ev</sub>	(kips)	619	619	1239	619	619	1239	1239	1239	619	619	310			
											Shaft	Settlement,	s, (in)	2/16	2/16	4/16	2/16	2/16	4/16	4/16	4/16	2/16	2/16	1/16			
											Ultimate Capacity	(Side Resistance	Only), Q <sub>u</sub> (kips)	1858.4	1858.4	3716.8	1858.4	1858.4	3716.8	3716.8	3716.8	1858.4	1858.4	929.2			
	%	ksi	ksi	ksi	ksi	ksi		B		nts	Settlement	Influence	Factor, I,	0.45	0.45	0.43	0.45	0.45	0.43	0.43	0.43	0.45	0.45	0.5			
	55	4.6	e	1600	280.0	3000	10.71	136.931	e	n Requiremen		Embedment	Ratio, L/D <sub>s</sub>	3.3	3.3	3.8	3.3	3.3	3.8	3.8	3.8	3.3	3.3	1.7			
onstants	gnation, RQD	(rock), qureat	ncrete), q <sub>ucono</sub>	ck core), E <sub>core</sub>	(mass), E <sub>mess</sub>	Young's Modulus (concrete), E <sub>o</sub>	E <sub>c</sub> /E <sub>mess</sub>	Resistance, f	Factor of Safety, FS	Braced Frame Foundation Requirements	Min. Vertical	Reinforcing,	0.01A <sub>6</sub> (ft <sup>2</sup> )	20.07	0.07	0.13	0.07	0.07	0.13	0.13	0.13	0.07	20.0	0.07			
Material Constants	Rock Quality Designation, RQD	ssion Strength	Strength (co	Young's Modulus (rock core), Ecore	Young's Modulus (rock mass), Eness	ng's Modulus		Ultimate Unit Side Resistance,	Facto	Braced Fra		Shaft Area,	A <sub>6</sub> (in <sup>2</sup> )	1018	1018	1810	1018	1018	1810	1810	1810	1018	1018	1018			
	Roc	Unconfined Compression Strength (rock), quoor Unconfined Compression Strength (concrete), quoor Vound's Modulus (rock core) Fucor	fined Compres	fined Compres	fined Compres	ed Compressio	Young'	Young's I	You		Ultin				Diameter of	Shaft, D <sub>s</sub> (ft)	е С	e	4	e	e	4	4	4	e	e	e7
		Uncor	Unconfine								Shaft Depth	Into Rock, L	(tt)	10	10	15	10	10	15	15	15	10	10	40			
											Max. Applied	beo	(ki ps)	518.3	504.2	1061.1	487.2	487.2	1004.6	1137.3	1065.0	429.0	429.0	250.0			
													Frame	F	2	e	4	5	9	2	8	6	10	OTHER			

Figure 5.2.3 Drilled Pier Design

# 6.0 Depth Analysis – Spanning the Lecture Hall

6.1 Existing System – Vierendeel Truss

The existing system uses a Vierendeel truss (Figure 2.6.1) to span 69-feet over the large lecture hall on the ground floor. The truss carries half of the lecture hall roof load as well as a 15-foot width of classroom spaces on the two upper stories and the main roof. A partial second floor framing plan, Figure 6.1.1, depicts how the truss is incorporated into the floor system. The truss utilizes rigidly connected vertical members to unite the three large girders into one great load carrying system. The truss uses vertical members instead of diagonal members to ensure that the exterior wall openings are not obstructed, thereby maintaining the symmetry of the main façade.

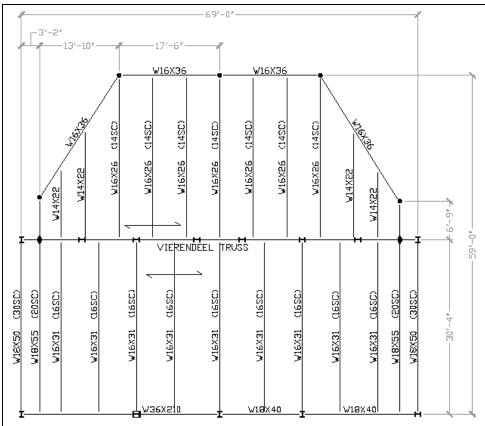


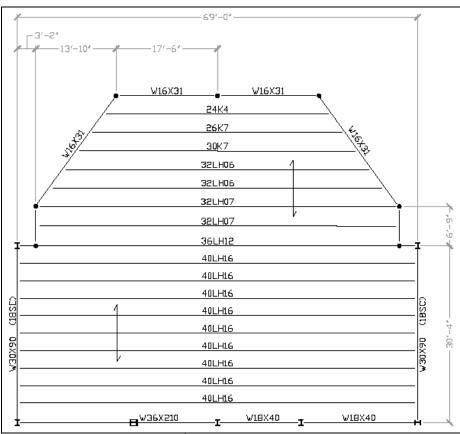
Figure 6.1.1 Partial 2<sup>nd</sup> Floor Framing Plan – Existing System

# 6.2 Alternative System – Long Span Steel Joists

This project has exposed me to the Vierendeel truss for the first time. Therefore, I took the opportunity to assess the effectiveness of this structural feature by designing an alternative that will fulfill the structural and architectural duties of the Vierendeel truss. This section will evaluate the structural requirements and Section 8 will discuss the architectural impact.

Three possible alternatives arose from a conversation with the building's primary structural engineer: (1) moving the lecture hall entirely into the main building envelope, (2) a 3-story diagonally braced truss and (3) a new floor diaphragm using long span steel joists. Since I did not want to alter the symmetrical façade or the interior space configuration, I was left with Option 3.

Using RAM Steel computer software and *The New Columbia Joist Company Catalog 2002-1*, I was able to design an alternative structural system (Figure 6.2.1) to span across the large lecture hall. However, the load carrying capacity of the joists precipitated an alteration of other floor diaphragm components. The steel joists, spaced approximately 3-feet center to center, must span the long direction, forcing the composite metal deck to be oriented in a direction perpendicular to the existing system. The long span joists must be a minimum of 40-inches deep to support the required dead and live loads across the entire span.



*Figure 6.2.1 Partial 2<sup>nd</sup> Floor Framing Plan – Long Span Joists* 

The purpose of designing the long span joist system was to determine if there was another system existed that could replace the Vierendeel truss system without dramatically changing the basic shape and configuration of the lecture hall space below. The joist system has the load-carrying ability to do just that. However, the architectural impact of the new design will ultimately decide its practicality as an alternative to the existing design.