Chapter 4 – Results and Discussion

4.1 General

Testing methods for this project consisted of loading to failure 150 single-shear bolted connections under reverse cyclic loading parallel to grain. The cyclic protocol was based on an additional 45 tests where the same connection configuration was monotonically loaded parallel to grain until failure. All tests had one row of five bolts. The test variable was the spacing between the bolts so as to investigate which spacing is most optimum. Three monotonic tests and 10 reverse cyclic tests were performed for each testing configuration, unless otherwise noted.

This chapter provides results for the monotonic and reverse cyclic tests. Load-displacement curves were produced for each test and analyzed to provide several parameters. The load-displacement plots can be seen in Appendices A and B. The reported parameters are maximum load and displacement, load and displacement at failure, load and displacement at forty percent of the maximum load, the equivalent elastic-plastic (E.E.P.) yield load and displacement, the load and displacement at five percent offset, elastic stiffness, slack, equivalent elastic-plastic (E.E.P.) energy, and ductility ratio. The results of material property testing are also presented. The reported parameters are moisture content (M.C.), specific gravity (S.G.), and yield and capacity from the dowel embedment (D.E.) tests. Explanations of the parameters and how they are determined can be found in Chapter 3.

Results are presented in tables with the series name as the heading. The "F" in the series name refers to the bolts size used in expected Yield Mode II tests of three-Fourths. The "H" in the series name refers to the bolt size used in the expected Yield Mode III tests of one-Half. The "E" in the series name refers to the bolt size used in the expected Yield Mode IV test of three-Eighths. The number refers to the bolt spacing. An eight refers to a spacing of eight times the bolt diameter (8D), a 7 refers to a spacing of seven times the bolt diameter (7D) and so forth. Test identification is illustrated in Figure 4.1.

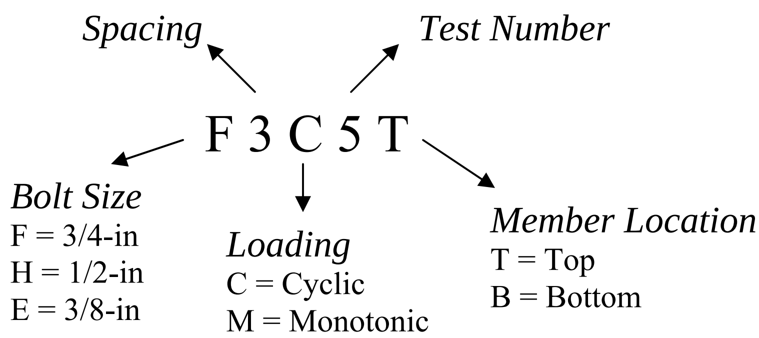

Figure 4.1: Test Identification.

The results are analyzed statistically to determine whether a statistical difference between the means of each spacing for several parameters exists. If a statistical difference is not present, then the smaller of the two compared spacings is considered more optimum because smaller spacing is more economic. Plots of the means are also examined to determine which of the spacings produces higher values for the means. According to the American Heritage Dictionary of the English Language (Houghton, 2000), optimum is defined as, “the point at which the condition, degree, or amount of something is the most favorable.” In this research several conditions need to be examined to make general statements as to which spacing is most optimal. These conditions are the overall maximum values of the means for the parameters examined, economy, and the statistical results determining whether the means are statistically different or whether the null hypothesis can not be rejected. The null hypothesis is that the compared means are statistically the same, therefore, if the null hypothesis is rejected than the compared means are statistically different. The optimal spacing is not based solely on which spacing produced the maximum value because there may not be a statistical difference between the spacing which produces the maximum value and the one which produces the second maximum value. For example, if Spacing A produced a slightly larger mean value than Spacing B but the statistical tests show that there is not a statistical difference between the two than A should not be chosen over B. Smaller spacings were judged to be more economic since less material would be utilized in smaller connections. Therefore, the decision as to whether A is more optimal than B is determined by which is the smaller spacing since no statistical difference was found between the results. No economic tests were performed.

4.2 Expected Yield Mode II

Testing for expected Yield Mode II consisted of two pieces of 2x6 Southern Yellow Pine lumber bolted with five 3/4 in. bolts. Additional information on the testing configuration can be found in Chapter 3.

4.2.1 Monotonic Test Results for Expected Yield Mode II

Fifteen multiple-bolt connections were loaded in compression until failure. No bolt bending was observed. Bolts rotated as the load was increased. Failure was due to the splitting of the member(s) through the end distance of 7D and was accompanied by the splitting of the member(s) along the line of bolts as the bolts rotated as illustrated in Figure 4.2. The connection behavior was expected to be Yield Mode II. Test results and material properties are shown in Tables 4.1 and 4.2 respectively. Three replications of the monotonic tests for each bolt spacing were performed unless otherwise noted.

Figure 4.2: Typical Expected Yield Mode II Connection under Monotonic Loading, 7D spacing.

Table 4.1: Monotonic Tests Results for Expected Yield Mode II.

	F8 Series*		F7 Series		F6 Series		F5 Series		F3 Series	
	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)
Max Load (lbs)	21675	24.3	21850	11.5	18350	8.03	16267	15.6	11567	7.86
@ Displ. (in)	0.709	56.2	0.665	32.5	0.455	31.2	0.428	10.7	0.375	6.11
Failure Load (lbs)	17275	23.9	17350	11.3	14017	3.08	12783	6.8	9183	8.55
@ Displ. (in)	0.753	41.8	0.791	22.6	0.646	31.3	0.652	11.6	0.650	30.7
40% Max (lbs)	8600	23.8	8700	11.1	7250	8.61	6450	15.4	4567	8.07
@ Displ. (in)	0.117	7.2	0.148	58.0	0.100	24.1	0.107	28.1	0.143	24.7
E.E.P. Yield (lbs)	17925	19.1	18367	6.3	15700	9.51	13983	15.6	9733	11.9
@ Displ. (in)	0.252	8.5	0.285	39.2	0.193	19.1	0.197	19.6	0.207	26.0
5% Offset (lbs)	12875	4.1	12567	7.4	13700	18.0	12933	14.2	10183	14.3
@ Displ. (in)	0.217	7.5	0.243	38.6	0.205	16.9	0.226	22.6	0.252	23.1
Elastic Stiff. (lb/in)	69075	5.0	72917	22.9	94533	21.6	84200	18.0	84167	20.6
Slack (in)	-0.007	-227.2	0.024	227.7	0.020	141	0.030	71.8	0.086	26.0
E.E.P. Energy (lb*in)	11700	64.1	11983	26.5	8717	39.4	7850	29.7	5433	42.4
Ductility Ratio	2.95	34.0	2.93	26.6	3.39	34.6	3.39	20.6	3.12	15.0

* Two Replications

E.E.P.: Equivalent Elastic-Plastic

Table 4.2: Properties for Monotonic Test Material for Expected Yield Mode II.

	F8 Series*		F7 Series		F6 Series		F5 Series		F3 Series	
Member Top	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)
M.C. (%)	13	25.7	13	10.4	14	2.52	15	3.92	12	6.40
S.G.	0.37	21.6	0.52	3.79	0.56	9.92	0.59	9.98	0.46	9.23
D.E. 5% Yield (psi)	4336	5.15	5125	14.1	4172	2.27	3236	18.4	4579	6.30
D.E. Capacity (psi)	4793	10.3	4943	11.1	3934	9.99	2793	22.6	4419	6.65

Member Bottom	F8 Series*		F7 Series		F6 Series		F5 Series		F3 Series	
M.C. (%)	15	7.38	14	15.5	14	15.9	14	8.92	12	15.8
S.G.	0.40	6.25	0.55	7.50	0.59	18.0	0.56	13.5	0.46	17.0
D.E. 5% Yield (psi)	3821	5.48	4837	17.2	4367	11.5	3987	10.1	4312	15.9
D.E. Capacity (psi)	3765	7.83	4189	13.7	3210	41.1	3853	12.3	3075	48.3

* Two Replications

M.C.: Moisture Content

S.G.: Specific Gravity

D.E.: Dowel Embedment

4.2.2 Cyclic Test Results for Expected Yield Mode II

Fifty multiple-bolt connections were subjected to a displacement controlled reverse cyclic protocol as described in Chapter 3. The reference deformation, Δ, obtained from monotonic testing was used to determine the magnitude of the loading cycles experienced by the connection in the cyclic testing. More explanation of the reference deformation can be found in Section 3.5.2 of Chapter 3. For the 8D spacing, Δ=0.45; for the 7D spacing, Δ=0.47; for the 6D spacing, Δ=0.39; for the 5D spacing, Δ=0.38; and for the 3D spacing, Δ=0.39. All bolts remained straight and rotated about the shear plane as expected for Yield Mode II. Failure was due to splitting of the member(s) through the end of the 7D distance and along the bolt line between bolts as illustrated in Figure 4.3. A typical load-deflection plot is shown in Figure 4.4. Test results and material properties are shown in Tables 4.3 and 4.4 respectively. Ten replications of the reverse cyclic tests for each bolt spacing were performed unless otherwise noted.

Figure 4.3: Typical Expected Yield Mode II Connection under Cyclic Loading, 5D spacing.

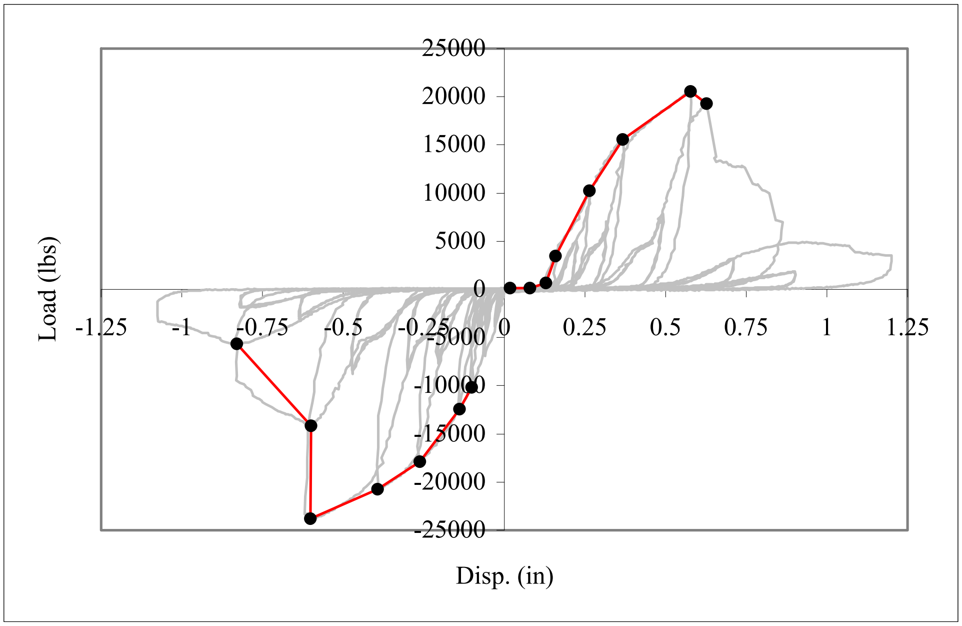

Figure 4.4: Typical Load-Deflection Plot for Expected Yield Mode II Connection.

Table 4.3: Cyclic Tests Results for Expected Yield Mode II.

	F8 Series		F7 Series		F6 Series		F5 Series		F3 Series	
	Mean	**COV(%)**	**Mean**	**COV(%)**	**Mean**	**COV(%)**	**Mean**	**COV(%)**	**Mean**	**COV(%)**
Max Load (lbs)	18520	14.9	21120	8.76	17110	10.7	13470	14.1	11130	12.6
@ Displ. (in))	0.456	44.3	0.501	14.3	0.375	19.2	0.293	17.0	0.260	15.6
Failure Load (lbs)	14805	14.9	16895	8.76	13685	10.7	10765	14.1	8910	12.6
@ Displ. (in)	0.485	39.3	0.519	12.4	0.414	13.3	0.323	16.8	0.308	20.3
40% Max (lbs)	5495	23.4	6270	15.47	4870	14.4	4155	19.6	3440	22.2
@ Displ. (in)	0.125	16.7	0.122	4.6	0.118	9.6	0.109	9.0	0.097	9.2
E.E.P. Yield (lbs)	15600	12.6	18065	7.87	14120	10.1	11430	11.3	9140	14.2
@ Displ. (in)	0.275	14.6	0.282	10.0	0.255	13.7	0.225	15.1	0.185	14.9
5% Offset (lbs)	15955	16.3	16890	7.32	15575	9.3	12530	16.7	10045	13.6
@ Displ. (in))	0.318	13.8	0.309	6.6	0.317	10.2	0.282	14.5	0.239	14.7
Elastic Stiff. (lb/in)	70920	17.1	76075	13.52	69785	15.9	66500	22.3	70885	32.8
Slack (in)	0.045	26.2	0.040	33.1	0.047	22.6	0.046	33.4	0.044	27.2
E.E.P. Energy (lb*in)	5550	62.1	6515	18.81	3930	20.9	2245	25.0	1915	39.6
Ductility Ratio	1.78	27.5	1.88	6.9	1.64	6.9	1.47	9.2	1.71	14.7

E.E.P.: Equivalent Elastic-Plastic

Table 4.4: Properties for Cyclic Test Material for Expected Yield Mode II.

	F8 Series		F7 Series		F6 Series		F5 Series		F3 Series*	
Member Top	**Mean**	**COV(%)**	**Mean**	**COV(%)**	**Mean**	**COV(%)**	**Mean**	**COV(%)**	**Mean**	**COV(%)**
M.C. (%)	13	20.4	14	3.46	15	7.72	14	6.00	15	5.40
S.G.	0.43	27.7	0.53	14.6	0.54	15.5	0.51	11.9	0.57	10.3
D.E. 5% Yield (psi)	3949	28.2	4248	15.1	4520	19.4	4395	14.0	4423	8.55
D.E. Capacity (psi)	3619	30.9	3961	24.78	4135	36.9	4127	19.7	4199	16.18

Member Bottom	**F8 Series**		**F7 Series**		**F6 Series**		**F5 Series**		**F3 Series***	
M.C. (%)	13	22.0	15	3.39	15	4.71	14	12.0	14	17.6
S.G.	0.45	19.5	0.59	8.14	0.54	11.7	0.51	14.7	0.50	27.9
D.E. 5% Yield (psi)	3757	21.6	4681	14.0	4333	16.4	4385	21.7	4935	10.4
D.E. Capacity (psi)	3360	30.1	4255	30.7	4130	18.6	4040	23.6	3792	30.3

* Eight Replications

M.C.: Moisture Content

S.G.: Specific Gravity

D.E.: Dowel Embedment

4.3 Expected Yield Mode III

Testing for expected Yield Mode III consisted of one piece of 4x6 Mixed Southern Yellow Pine lumber and a 0.25 in. metal plate bolted with five 1/2 in. bolts. Additional information on the testing configuration can be found in Chapter 3.

4.3.1 Monotonic Test Results

Fifteen multiple-bolt connections were loaded in compression until failure. Slight bolt bending was observed in some of the bolts which would be indicative of the formation of a plastic hinge. Connections with larger bolt spacing exhibited more bolt bending. For Yield Mode III, bolt bending was expected for all bolts in all tests as they formed a plastic hinge. However, the connections behaved more like Yield Mode II where bolts rotate around the shear plane. Failure was due to splitting of the wood member(s) through the end distance of 7D and was accompanied by the splitting of the wood member(s) along the line of bolts as the bolts rotated. The connection configuration is illustrated in Figure 4.5. Test results and material properties are shown in Tables 4.5 and 4.6 respectively. Three replications of the monotonic tests for each bolt spacing were performed unless otherwise noted.

Figure 4.5: Typical Expected Yield Mode III Connection under Monotonic Loading, 6D spacing.

Table 4.5: Monotonic Tests Results for Expected Yield Mode III.

	H8 Series		H7 Series		H6 Series		H5 Series		H3 Series	
	Mean	**COV(%)**	**Mean**	**COV(%)**	**Mean**	**COV(%)**	**Mean**	**COV(%)**	**Mean**	**COV(%)**
Max Load (lbs)	22617	6.14	22700	12.3	15283	19.2	18433	15.4	10850	16.8
@ Displ. (in)	0.450	9.16	0.690	13.4	0.263	10.3	0.335	49.5	0.297	28.1
Failure Load (lbs)	18033	6.13	18083	12.5	11900	18.7	14717	15.2	8667	16.9
@ Displ. (in)	0.832	59.0	0.726	16.8	0.332	39.5	0.444	21.4	0.471	57.5
40% Max (lbs)	8917	5.89	9050	12.7	6033	19.2	7333	14.4	4283	16.4
@ Displ. (in)	0.161	17.6	0.190	6.3	0.155	20.0	0.094	64.7	0.117	51.1
E.E.P. Yield (lbs)	18683	7.74	18417	12.7	12217	19.2	16300	20.6	9117	19.2
@ Displ. (in)	0.260	9.78	0.296	4.5	0.216	13.6	0.198	39.3	0.185	25.1
5% Offset (lbs)	17367	4.52	15200	9.3	14583	19.7	15467	22.1	9967	16.0
@ Displ. (in)	0.273	16.4	0.286	6.9	0.265	9.9	0.214	30.8	0.222	28.3
Elastic Stiff. (lb/in)	99633	8.85	88467	12.9	104600	25.7	89600	39.5	71150	4.3
Slack (in)	0.071	42.8	0.088	13.1	0.097	35.8	0.005	631	0.057	111
E.E.P. Energy (lb*in)	13217	73.2	10550	20.7	2200	52.9	5533	16.3	3550	93.8
Ductility Ratio	3.19	56.2	2.45	13.6	1.52	31.1	2.34	16.6	2.94	84.3

E.E.P.: Equivalent Elastic-Plastic

Table 4.6: Properties for Monotonic Test Material for Expected Yield Mode III.

	H8 Series		H7 Series		H6 Series		H5 Series		H3 Series	
Member Bottom	**Mean**	**COV(%)**	**Mean**	**COV(%)**	**Mean**	**COV(%)**	**Mean**	**COV(%)**	**Mean**	**COV(%)**
M.C. (%)	14	1.90	14	13.7	15	4.17	14	2.38	14	10.5
S.G.	0.18	10.2	0.22	17.1	0.26	3.67	0.29	5.64	0.29	15.7
D.E. 5% Yield (psi)	10143	5.16	4080	21.8	3954	14.3	4597	31.8	4728	23.3
D.E. Capacity (psi)	9927	3.23	3900	19.9	3526	9.0	3740	27.6	4347	18.9

M.C.: Moisture Content

S.G.: Specific Gravity

D.E.: Dowel Embedment

4.3.2 Cyclic Test Results

Fifty multiple-bolt connections were subjected to a displacement controlled reverse cyclic protocol as described in Chapter 3. The reference deformation, Δ, obtained from monotonic testing was used to determine the magnitude of the loading cycles experienced by the connection in the cyclic testing. More explanation of the reference deformation can be found in Section 3.5.2 of Chapter 3. For the 8D spacing, Δ=0.49; for the 7D spacing, Δ=0.43; for the 6D spacing, Δ=0.20; for the 5D spacing, Δ=0.26; and for the 3D spacing, Δ=0.28. Most bolts remained straight and rotated about the shear plane which is not expected for Yield Mode III. Only three connection tests exhibited any signs of bolt bending. A single plastic hinge was expected to be formed in all bolts in all tests. Failure was due to splitting of the wood member(s) through the end of the 7D distance and along the bolt line between bolts as illustrated in Figure 4.6. A typical load-deflection plot is shown in Figure 4.7. Test results and material properties are shown in Tables 4.7 and 4.8 respectively. Ten replications of the reverse cyclic tests for each bolt spacing were performed unless otherwise noted.

Figure 4.6: Typical Expected Yield Mode III Connection under Cyclic Loading, 3D spacing.

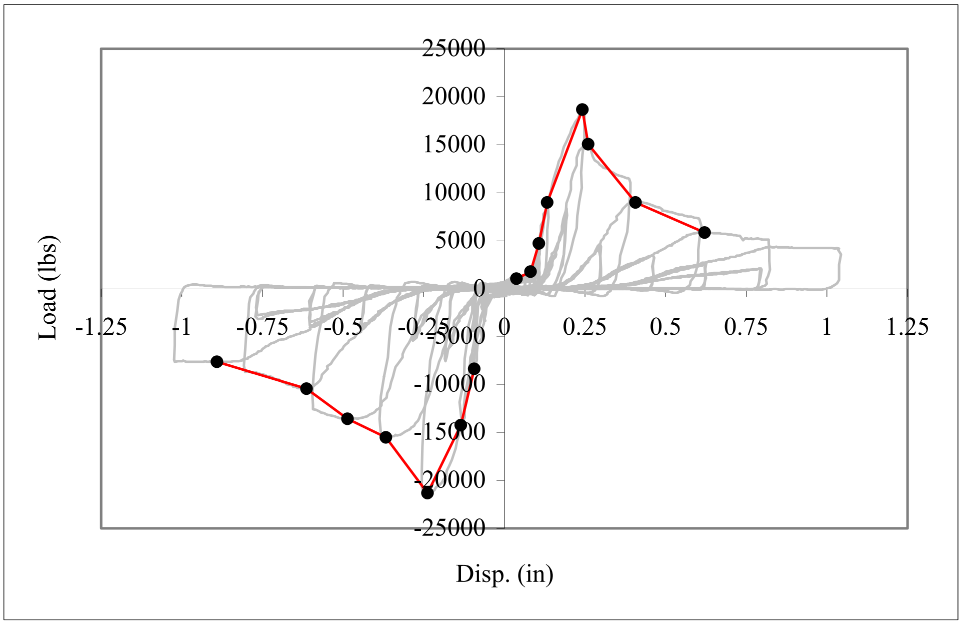

Figure 4.7: Typical Load-Deflection Plot for Expected Yield Mode III.

Table 4.7: Cyclic Tests Results for Expected Yield Mode III.

	H8 Series		H7 Series		H6 Series		H5 Series		H3 Series	
	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)
Max Load (lbs)	19970	14.6	18600	22.4	17610	21.3	14505	17.2	9530	34.5
@ Displ. (in)	0.469	31.8	0.396	35.2	0.350	18.7	0.320	17.9	0.285	20.6
Failure Load (lbs)	15980	14.7	14880	22.4	14085	21.3	11600	17.2	7620	34.5
@ Displ. (in)	0.546	25.2	0.475	26.0	0.395	7.4	0.383	14.5	0.383	14.7
40% Max (lbs)	6835	13.7	5455	27.8	3980	48.8	3385	28.3	2590	41.0
@ Displ. (in)	0.135	12.7	0.113	10.0	0.099	23.3	0.097	22.7	0.078	24.8
E.E.P. Yield (lbs)	17040	15.7	15520	22.7	14240	20.2	11790	17.1	8050	35.4
@ Displ. (in)	0.283	18.8	0.237	17.9	0.215	18.0	0.221	21.1	0.175	24.0
5% Offset (lbs)	15720	11.6	14320	25.5	13990	17.1	11595	16.8	8205	41.3
@ Displ. (in)	0.294	19.5	0.251	15.1	0.241	16.2	0.253	23.2	0.207	24.3
Elastic Stiff. (lb/in)	72505	23.8	84755	22.3	91930	21.5	73820	35.3	63120	27.0
Slack (in)	0.036	42.2	0.046	38.8	0.053	20.2	0.047	30.0	0.038	48.8
E.E.P. Energy (lb*in)	6950	40.9	5465	39.1	3910	21.3	2985	21.8	2180	41.2
Ductility Ratio	1.94	19.3	2.06	22.5	1.91	13.4	1.79	13.2	2.30	30.2

E.E.P.: Equivalent Elastic-Plastic

Table 4.8: Material Properties for Cyclic Tests Results for Expected Yield Mode III.

	H8 Series		H7 Series		H6 Series		H5 Series		H3 Series	
Member Bottom	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)
M.C. (%)	14	7.87	15	4.71	14	14.8	13.8	6.77	15	5.51
S.G.	0.20	14.7	0.23	19.0	0.24	18.3	0.29	15.9	0.29	13.0
D.E. 5% Yield (psi)	3903	55.7	4554	20.1	4215	25.4	3604	19.4	4105	24.9
D.E. Capacity (psi)	4970	57.7	4353	25.3	3937	21.6	3407	22.8	4030	21.5

M.C.: Moisture Content

S.G.: Specific Gravity

D.E.: Dowel Embedment

4.4 Expected Yield Mode IV

Testing for expected Yield Mode IV consisted of two pieces of 2x6 Southern Yellow Pine lumber bolted with five 3/8 in. bolts. Additional information on the testing configuration can be found in Chapter 3.

4.4.1 Monotonic Test Results

Fifteen multiple-bolt connections were loaded in compression until failure. Slight bolt bending was observed in some bolts which would be indicative of the formation of a plastic hinge. Five tests showed signs that a single plastic hinge was formed in some of the bolts and two tests showed signs that two plastic hinges were formed in some of the bolts. This is not expected of Yield Mode IV. Bolt bending was expected for all bolts in all tests as they formed two plastic hinges. Therefore, the connection behaved more like Yield Mode II where bolts rotate around the shear plane. Failure was due to the splitting of the member(s) through the end distance of 7D and was accompanied by the splitting of the member(s) along the line of bolts as the bolts rotated as illustrated in Figure 4.8. Test results and material properties are shown in Tables 4.9 and 4.10 respectively. Three replications of the monotonic tests for each bolt spacing were performed unless otherwise noted.

Figure 4.8: Typical Expected Yield Mode IV Connection under Monotonic Loading, 3D spacing.

Table 4.9: Monotonic Tests Results for Expected Yield Mode IV.

	E8 Series		E7 Series		E6 Series		E5 Series		E3 Series	
	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)
Max Load (lbs)	8767	19.9	8950	14.5	7767	10.8	7067	3.49	6133	9.66
@ Displ. (in)	0.556	44.6	0.558	40.3	0.479	18.7	0.445	8.77	0.291	22.3
Failure Load (lbs)	6833	22.9	7133	14.2	6183	11.0	5633	3.36	4783	7.91
@ Displ. (in)	0.751	28.4	0.706	31.7	0.658	15.8	0.608	7.46	0.390	22.2
40% Max (lbs)	3483	19.9	3533	13.9	3100	11.2	2800	4.72	2400	9.08
@ Displ. (in)	0.129	36.9	0.110	18.2	0.113	27.0	0.148	15.12	0.085	33.0
E.E.P. Yield (lbs)	7467	16.9	7867	10.0	6667	13.2	5867	5.55	5467	13.76
@ Displ. (in)	0.246	27.4	0.230	9.8	0.210	14.3	0.234	13.88	0.172	17.7
5% Offset (lbs)	5133	14.1	5717	5.8	4733	1.6	4933	5.10	4950	7.63
@ Displ. (in)	0.198	24.6	0.190	8.5	0.179	26.4	0.230	16.67	0.177	20.4
Elastic Stiff. (lb/in)	34350	7.2	35900	4.8	37100	14.1	36267	20.70	36000	21.1
Slack (in)	0.028	86.0	0.011	128.0	0.030	95.4	0.069	24.81	0.017	163.0
E.E.P. Energy (lb*in)	4850	42.9	4767	47.0	3750	31.9	2883	17.37	1633	20.38
Ductility Ratio	3.08	23.2	3.04	25.0	3.23	29.6	2.65	22.77	2.25	5.8

E.E.P.: Equivalent Elastic-Plastic

Table 4.10: Properties for Monotonic Test Material for Expected Yield Mode IV.

	E8 Series		E7 Series		E6 Series		E5 Series		E3 Series	
Member Top	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)
M.C. (%)	14	15.9	14	3.71	15	0.77	12	8.59	15	7.37
S.G.	0.53	15.4	0.54	4.34	0.66	21.3	0.55	13.7	0.63	12.2
D.E. 5% Yield (psi)	5810	10.3	4983	10.0	4873	5.86	5383	12.9	5025	21.2
D.E. Capacity (psi)	6072	12.3	4961	11.4	4966	5.23	5341	13.3	4938	17.7

Member Bottom	E8 Series		E7 Series		E6 Series		E5 Series		E3 Series	
M.C. (%)	15	2.71	14	7.25	15	0.16	14	7.83	14	4.95
S.G.	0.61	10.7	0.57	7.54	0.64	3.84	0.67	15.6	0.58	7.21
D.E. 5% Yield (psi)	5020	10.7	5571	21.8	5490	13.6	5642	6.51	5624	27.8
D.E. Capacity (psi)	5085	15.9	5848	31.0	5536	12.8	5662	6.02	5847	29.4

M.C.: Moisture Content

S.G.: Specific Gravity

D.E.: Dowel Embedment

4.4.2 Cyclic Test Results

Fifty multiple-bolt connections were subjected to a displacement controlled reverse cyclic protocol as described in Chapter 3. The reference deformation, Δ, obtained from monotonic testing was used to determine the magnitude of the loading cycles experienced by the connection in the cyclic testing. More explanation of the reference deformation can be found in Section 3.5.2 of Chapter 3. For the 8D spacing, Δ=0.45; for the 7D spacing, Δ=0.41; for the 6D spacing, Δ=0.39; for the 5D spacing, Δ=0.36; and for the 3D spacing, Δ=0.23. The connections behaved more like Yield Mode II where bolts remain straight and rotate around the shear plane. Nine connection tests exhibited some signs of bolt bending, however, the bending was from a single plastic hinge rather than two plastic hinges which is expected for Yield Mode IV. Failure was due to splitting of the wood member(s) through the end of the 7D distance and along the bolt line between bolts as illustrated in Figure 4.9. A typical load-deflection plot is shown in Figure 4.10. Test results and material properties are shown in Tables 4.11 and 4.12 respectively. Ten replications of the reverse cyclic tests for each bolt spacing were performed unless otherwise noted.

Figure 4.9: Typical Expected Yield Mode IV Connection under Cyclic Loading, 5D spacing.

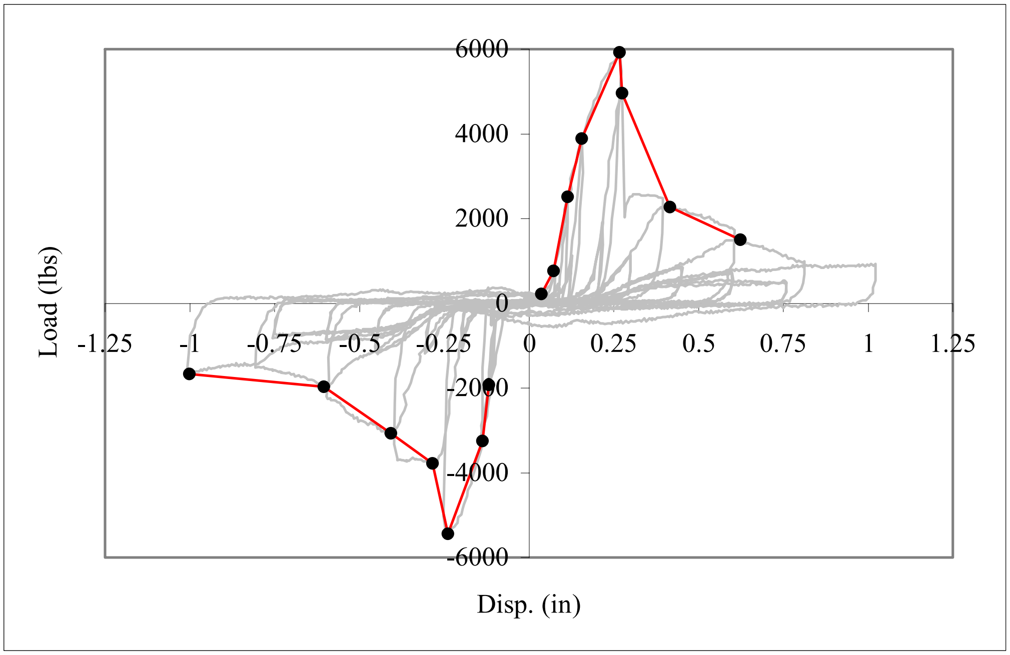

Figure 4.10: Typical Load-Deflection Plot for Expected Yield Mode IV.

Table 4.11: Cyclic Tests Results for Expected Yield Mode IV.

	E8 Series		E7 Series		E6 Series		E5 Series		E3 Series	
	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)
Max Load (lbs)	7825	11.8	6860	26.4	6260	18.1	5605	16.7	4550	17.4
@ Displ. (in)	0.454	25.0	0.380	32.9	0.317	15.8	0.287	10.4	0.236	14.7
Failure Load (lbs)	6255	11.9	5485	26.4	5010	17.9	4495	16.7	3650	17.5
@ Displ. (in)	0.483	21.2	0.423	30.3	0.350	11.6	0.311	8.3	0.292	11.9
40% Max (lbs)	2530	16.1	2105	39.8	1790	27.1	1695	19.1	1115	43.7
@ Displ. (in)	0.131	8.7	0.110	16.5	0.108	10.5	0.107	10.3	0.086	14.4
E.E.P. Yield (lbs)	6490	11.0	5700	24.5	5205	18.8	4595	15.5	3845	18.5
@ Displ. (in)	0.255	15.1	0.207	18.6	0.212	13.1	0.196	10.2	0.169	14.7
5% Offset (lbs)	5370	15.6	4560	18.8	4845	22.1	4565	14.6	4130	23.2
@ Displ. (in)	0.244	14.4	0.205	21.7	0.224	11.5	0.218	14.9	0.196	14.3
Elastic Stiff. (lb/in)	33610	20.9	41080	29.7	34035	21.4	33695	18.3	34925	20.8
Slack (in)	0.051	26.6	0.056	23.2	0.055	20.1	0.054	16.4	0.053	10.7
E.E.P. Energy (lb*in)	2215	31.1	1820	62.0	1175	27.3	890	21.5	745	21.3
Ductility Ratio	1.92	17.0	2.08	29.1	1.71	9.2	1.62	10.5	1.77	16.4

E.E.P.: Equivalent Elastic-Plastic

Table 4.12: Properties for Cyclic Test Material for Expected Yield Mode IV.

	E8 Series		E7 Series		E6 Series		E5 Series		E3 Series	
Member Top	**Mean**	**COV(%)**	**Mean**	**COV(%)**	**Mean**	**COV(%)**	**Mean**	**COV(%)**	**Mean**	**COV(%)**
M.C. (%)	15	8.84	13	8.17	12	8.58	14	10.3	14	8.10
S.G.	0.60	9.51	0.59	14.0	0.53	12.5	0.61	11.3	0.62	13.0
D.E. 5% Yield (psi)	4870	24.8	4796	26.6	5688	11.0	5120	20.0	5517	20.3
D.E. Capacity (psi)	4926	26.9	4673	25.7	5703	10.6	5072	19.9	5578	24.0

Member Bottom	**E8 Series**		**E7 Series**		**E6 Series**		**E5 Series**		**E3 Series**	
M.C. (%)	14	7.28	15	14.8	13	17.4	14	6.43	14	4.81
S.G.	0.59	8.32	0.64	19.0	0.55	27.5	0.53	17.8	0.60	13.8
D.E. 5% Yield (psi)	5182	19.8	4750	11.0	5105	22.4	5392	23.7	4731	18.9
D.E. Capacity (psi)	5281	23.8	4707	14.0	5002	25.6	5260	24.6	4592	31.5

M.C.: Moisture Content

S.G.: Specific Gravity

D.E.: Dowel Embedment

4.5 Bolt Testing Results

The minimum yield strength of a SAE J429 Grade 2 is 57,000 psi as specified by the manufacturer based on tension tests of the bolt (SAE, 1999). The three bolt sizes used in the connection tests were tested for yield strength and analyzed according to procedures found in Section 3.6.3 of Chapter 3 where a bending test was utilized. Fifteen replications for each bolt size were performed.

Table 4.13: Bolt Testing Results.

	F Series		H Series		E Series	
	Mean	**COV (%)**	**Mean**	**COV (%)**	**Mean**	**COV (%)**
Yield Strength (psi)	55451.2	13.0	61297.8	17.1	68612.8	10.9

4.6 Statistical Analysis

To make inferences whether the spacing between bolts affects strength and serviceability parameters, statistical analysis was performed on the tests that underwent reverse cyclic loading. It was assumed that the data is normally distributed and the standard deviations are equal. A significance level of α=0.05 was used to test the null hypothesis, H_o, that any two means are equal. The analysis of variance (ANOVA) was used to compare data and determine whether the means for several parameters for each connection layout are statistically different. For example, the results for 8D, 7D, 6D, 5D, and 3D spacing for the expected Yield Mode II connection configuration for the maximum load parameter were compared. The results of the ANOVA test can be seen in Table 4.14. The F value was compared to the $F_{critical}$ value. If F is larger than $F_{critical}$ than there is a statistical difference between the means and the null hypothesis is rejected for the group of spacings. Further testing is then needed to determine which spacings are different. If F is smaller than $F_{critical}$ than there is not a statistical difference between the means and the null hypothesis is not rejected. Further testing among the spacings is not required. Thus for the sample results given in Table 4.14, the null hypothesis is rejected because the F value is larger than the $F_{critical}$ which is labeled as "F crit".

Table 4.14: Sample ANOVA Results.

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
8D	10	185210	18521	7612050
7D	10	211191	21119	3408100
6D	10	171037	17103	3339377
5D	10	134621	13462	3607798
3D	10	111387.32	11138.7	1975115

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	634906138	4	1.6E+08	39.8	3.09E-14	2.58
Within Groups	179481965	45	3988488			
Total	814388104	49				

Additional testing is performed when the ANOVA results in a rejection of the null hypothesis. The Tukey method allows for multiple comparisons within a group. The following calculations are required for the Tukey method:

$$T = \frac{1}{\sqrt{2}} * q(1-\alpha, r, n_T - r) \tag{4.1}$$

where: $1 - \alpha$ = family confidence coefficient

r = total number of factor levels in the study

n_T = total number of observations in the study

Note that $q(1-\alpha,r,n_T-r)$ is taken from statistical tables given the values for the $1-\alpha$, r, and n_T-r parameters.

$$S(D) = \left[\frac{2*MSE}{n}\right]^{1/2} \qquad (4.2)$$

where: MSE = error mean square

n = number of repetitions

The product of T and s(D) is compared to the difference in the means of the two spacings that are being compared. If the difference in the means is larger than the product of T and s(D) than the null hypothesis is rejected indicating that a statistical difference between the means exists. If the difference is smaller, than the null hypothesis that the means are the same can not be rejected.

4.6.1 Expected Yield Mode II Connection Configuration

The data and the mean of seven parameters for the five spacings tested using the expected Yield Mode II connection configuration are plotted in Figures 4.11 through 4.17. The results for the Tukey tests which determines whether the null hypothesis can be rejected or not for the seven parameters are tabulated in Tables 4.15 through 4.20. Tukey tests were not performed when the ANOVA test determined that the null hypothesis could not be rejected indicating that a statistical difference in the means is not present. Appendix C provides the calculations for the ANOVA and Tukey tests.

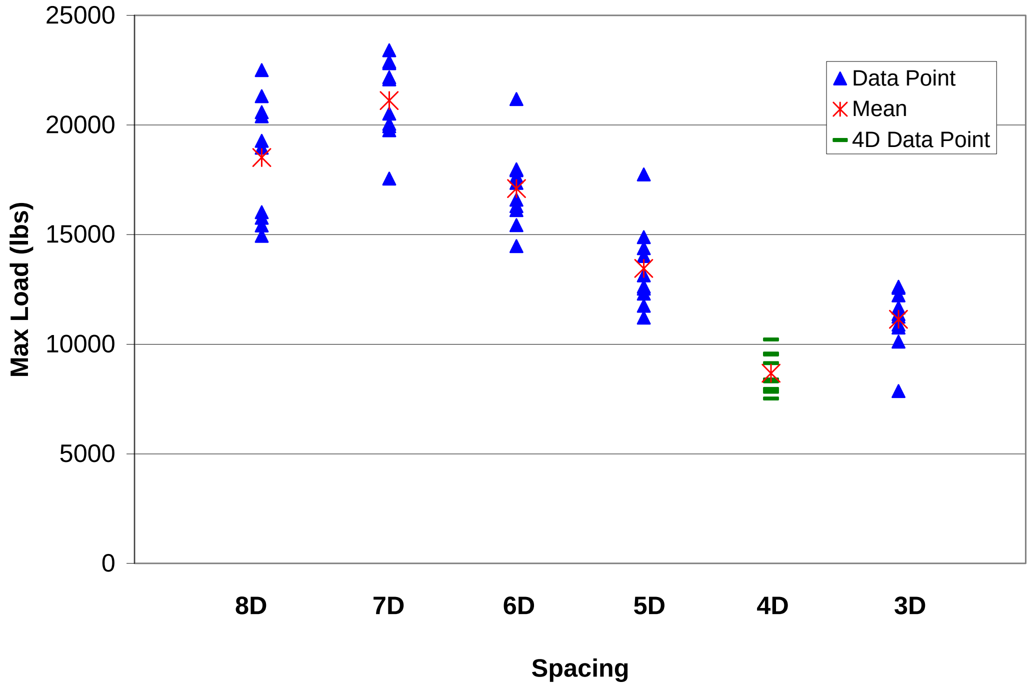

Figure 4.11: Maximum Loads and Means for Expected Yield Mode II Cyclic Tests with Data from Anderson (2002) for 4D Spacing.

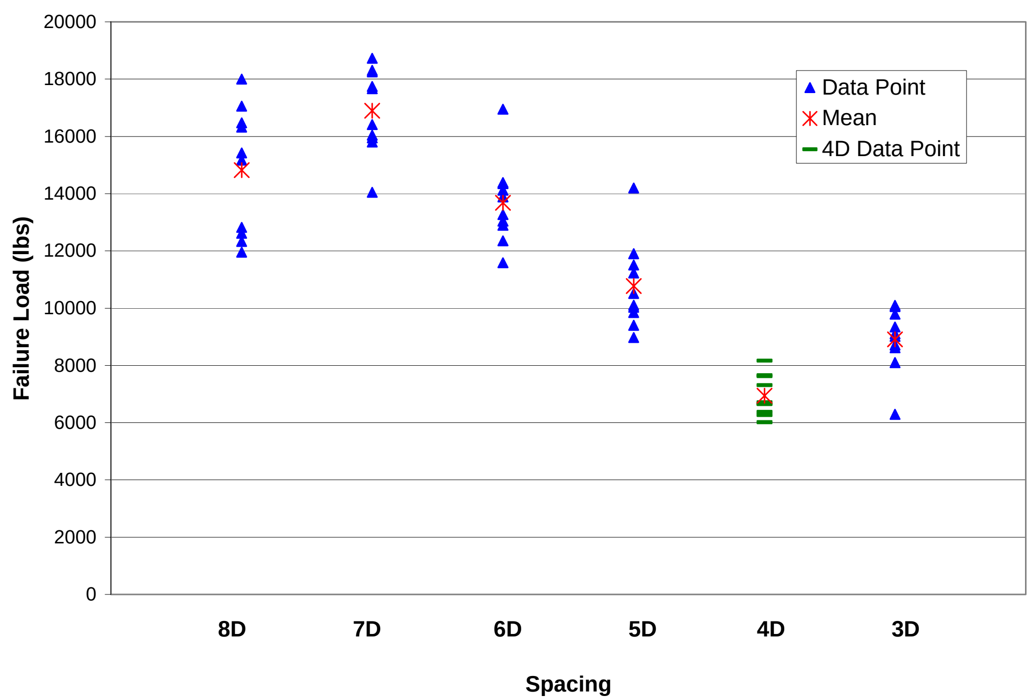

Figure 4.12: Failure Loads and Means for Expected Yield Mode II Cyclic Tests with Data from Anderson (2002) for 4D Spacing.

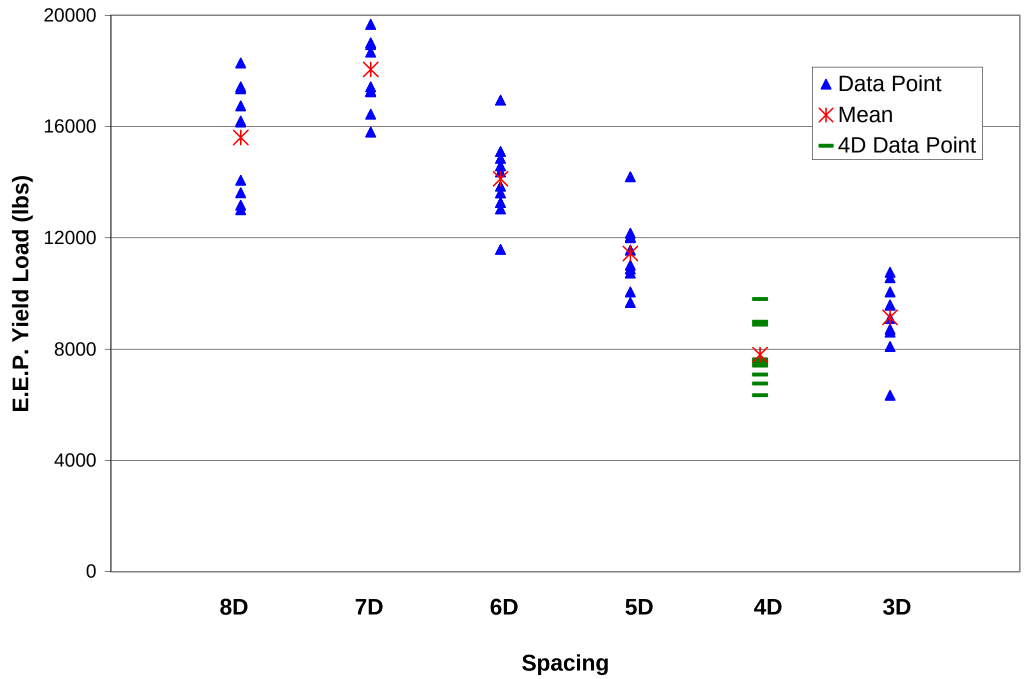

Figure 4.13: E.E.P. Yield Loads and Means for Expected Yield Mode II Cyclic Tests with Data from Anderson (2002) for 4D Spacing.

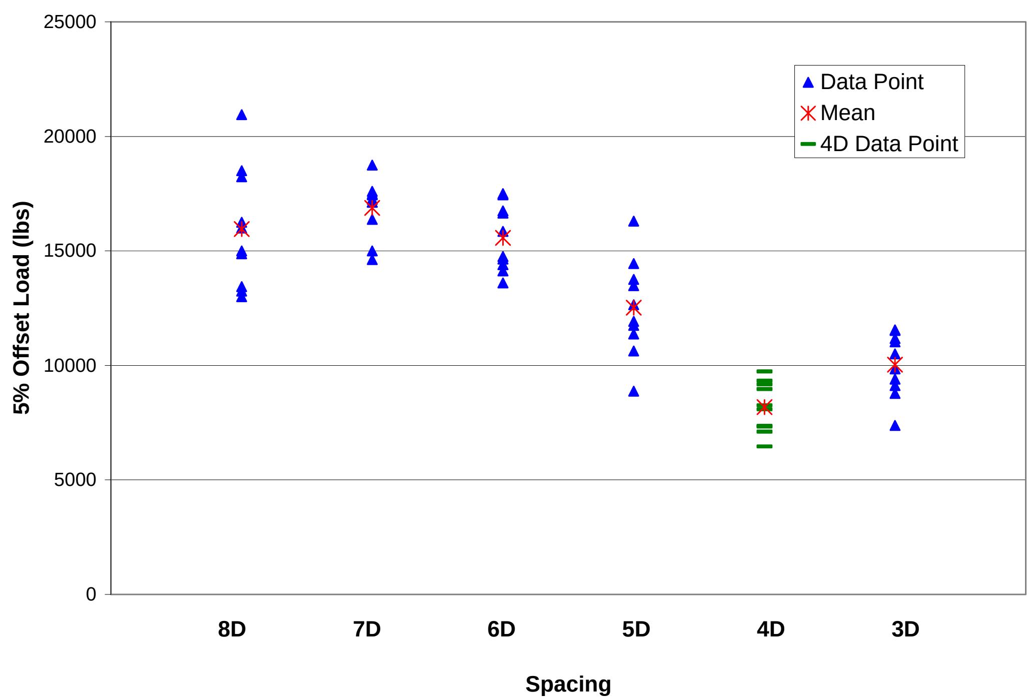

Figure 4.14: 5% Offset Loads and Means for Expected Yield Mode II Cyclic Tests with Data from Anderson (2002) for 4D Spacing.

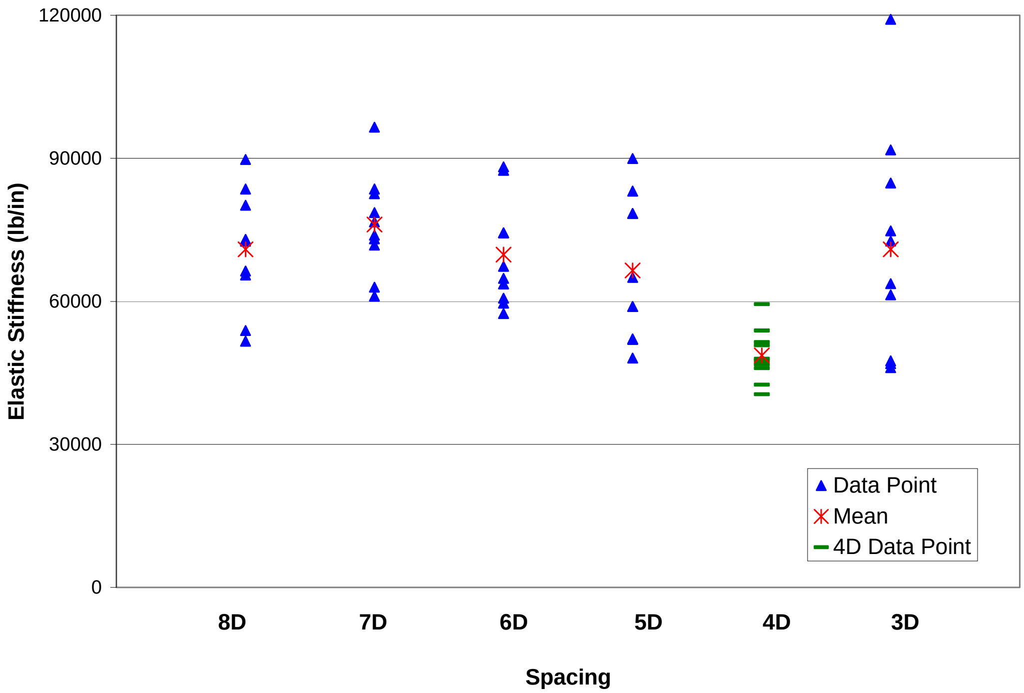

Figure 4.15: Elastic Stiffness and Means for Expected Yield Mode II Cyclic Tests with Data from Anderson (2002) for 4D Spacing.

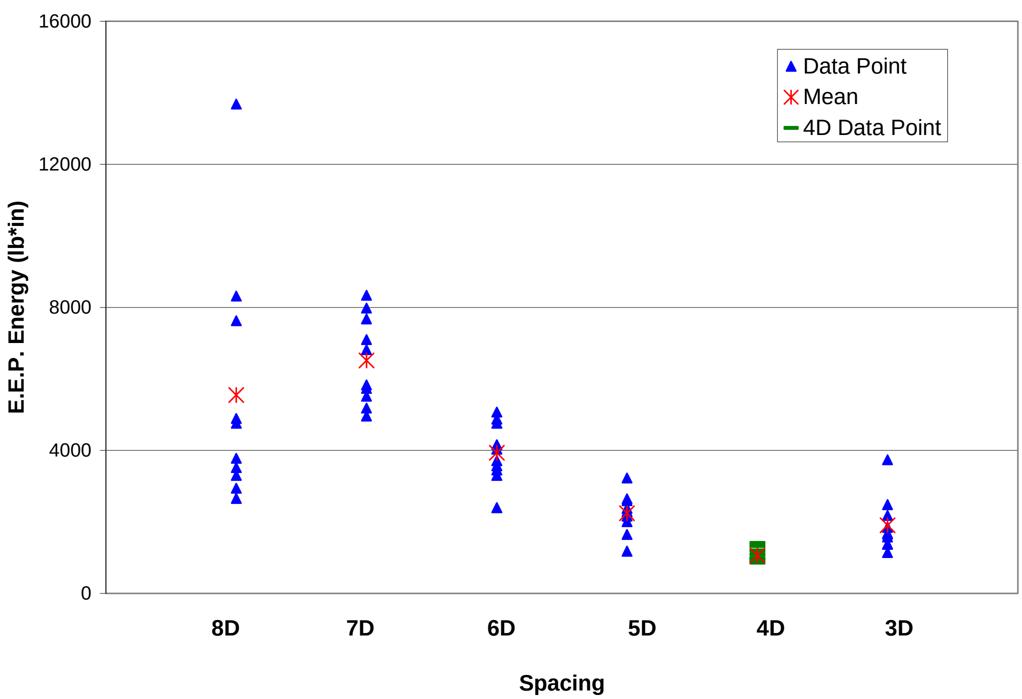

Figure 4.16: E.E.P. Energy and Means for Expected Yield Mode II Cyclic Tests with Data from Anderson (2002) for 4D Spacing.

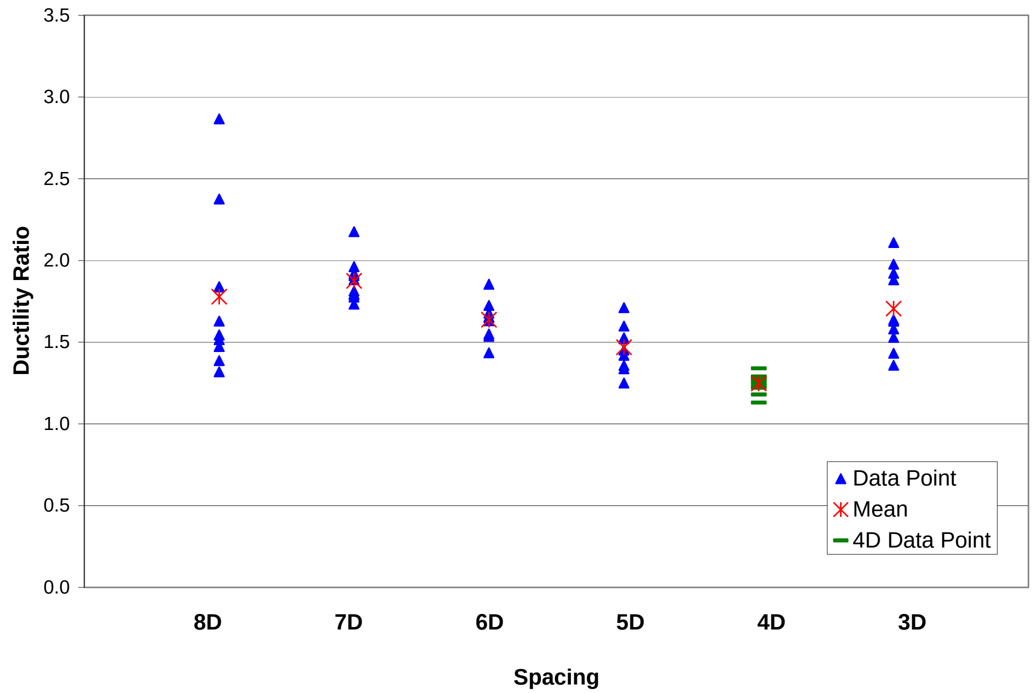

Figure 4.17: Ductility Ratio and Means for Expected Yield Mode II Cyclic Tests with Data from Anderson (2002) for 4D Spacing.

Table 4.15: Tukey Results for Maximum Load for Expected Yield Mode II Cyclic Tests.

Max Load	8D	7D	6D	5D	3D
8D	0	0	0	0	0
7D	Reject Ho	0	0	0	0
6D	C.R. Ho	Reject Ho	0	0	0
5D	Reject Ho	Reject Ho	Reject Ho	0	0
3D	Reject Ho	Reject Ho	Reject Ho	C.R. Ho	0

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.16: Tukey Results for Failure Load for Expected Yield Mode II Cyclic Tests.

Failure Load	8D	7D	6D	5D	3D
8D	0				
7D	Reject Ho	0			
6D	C.R. Ho	Reject Ho	0		
5D	Reject Ho	Reject Ho	Reject Ho	0	
3D	Reject Ho	Reject Ho	Reject Ho	C.R. Ho	0

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.17: Tukey Results for E.E.P. Yield Load for Expected Yield Mode II Cyclic Tests.

Yield Load	**8D**	**7D**	**6D**	**5D**	**3D**
8D	0				
7D	Reject Ho	0			
6D	C.R. Ho	Reject Ho	0		
5D	Reject Ho	Reject Ho	Reject Ho	0	
3D	Reject Ho	Reject Ho	Reject Ho	Reject Ho	0

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.18: Tukey Results for 5% Offset Load for Expected Yield Mode II Cyclic Tests.

5% Offset Load	**8D**	**7D**	**6D**	**5D**	**3D**
8D	0	0	0	0	0
7D	C.R. Ho	0	0	0	0
6D	C.R. Ho	C.R. Ho	0	0	0
5D	Reject Ho	Reject Ho	Reject Ho	0	0
3D	Reject Ho	Reject Ho	Reject Ho	Reject Ho	0

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.19: Tukey Results for E.E.P. Energy for Expected Yield Mode II Cyclic Tests.

E.E.P. Energy	**8D**	**7D**	**6D**	**5D**	**3D**
8D	0				
7D	C.R. Ho	0			
6D	C.R. Ho	Reject Ho	0		
5D	Reject Ho	Reject Ho	C.R. Ho	0	
3D	Reject Ho	Reject Ho	C.R. Ho	C.R. Ho	0

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.20: Tukey Results for Ductility Ratio for Expected Yield Mode II Cyclic Tests.

Ductility Ratio	**8D**	**7D**	**6D**	**5D**	**3D**
8D	0				
7D	C.R. Ho	0			
6D	C.R. Ho	C.R. Ho	0		
5D	C.R. Ho	Reject Ho	C.R. Ho	0	
3D	C.R. Ho	C.R. Ho	C.R. Ho	C.R. Ho	0

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

As indicated in Table 4.15 the null hypothesis can not be rejected for two mean comparisons for the maximum load parameter; 8D compared to 6D and 5D compared to 3D. Therefore, the 8D, 7D, and 6D spacing are more optimal than the 5D and 3D spacing since the larger spacings resulted in larger mean values. From Figure 4.11, it can be seen that the 7D spacing had the largest mean value. Thus, the 7D spacing is determined to be most optimal for the maximum load parameter for the expected Yield Mode II cyclic tests.

The null hypothesis was rejected for most of the means for the failure load parameter. The null hypothesis could not be rejected for two comparisons: 8D compared to 6D, and 5D compared to 3D. From Figure 4.12, it can be seen that the 7D spacing had the largest mean value. Thus, the 7D spacing is determined to be most optimal for the failure load parameter for the expected Yield Mode II cyclic tests.

From the statistical analysis, the means for each of the spacings for the E.E.P. yield load parameter are all statistically different except the 8D and 6D spacing where the null hypothesis that the means are the same can not be rejected as indicated in Table 4.17. Therefore, the 8D, 7D, and 6D spacing are more optimal than the 5D and 3D spacing since the larger spacings resulted in larger mean values. From Figure 4.13, it can be seen that the 7D spacing had the largest mean value. Thus, the 7D spacing is determined to be most optimal for the E.E.P. yield load parameter for the expected Yield Mode II cyclic tests.

The 5% offset load results showed most of the means to be statistically different except the 8D, 7D, and 6D spacing comparisons as indicated in Table 4.18. Therefore, the 8D, 7D, and 6D spacing are more optimal than the 5D and 3D spacing since the larger spacings resulted in larger mean values. Among the 8D, 7D, and 6D spacings, the 6D spacing is concluded to be the most optimum for the 5% offset load parameter for the expected Yield Mode II cyclic tests because smaller spacings are more economic.

The results for the ANOVA test for the elastic stiffness parameter showed that the null hypothesis can not be rejected for any of the mean comparisons. Therefore, the Tukey test was not performed on the multiple comparisons. A clear determination as to which spacing performed better for the elastic stiffness parameter for the expected Yield Mode II cyclic tests can not be made. The results suggest that the elastic stiffness parameter is not affected by spacing but rather it is a function of the fastener bearing on the wood material only.

As indicated in Table 4.19, half of the means for the E.E.P. energy parameter are statistically different. The null hypothesis could not be rejected for 8D compared to 7D, 8D compared to 6D, 6D compared to 5D, 6D compared to 3D, and 5D compared to 3D. From Figure 4.16, it can be seen that the 7D spacing had the largest mean value. The mean for the 8D spacing is not considered statistically different, however, one outlier exists in the data as seen in Figure 4.16. The 7D spacing is also smaller, thus, more economic than the 8D spacing. Therefore, the 7D spacing is determined to be most optimal for the E.E.P. energy parameter for the expected Yield Mode II cyclic tests.

The null hypothesis could not be rejected for most of the means for the ductility ratio parameter. Only one mean is considered statistically different; 7D compared to 5D. A clear determination as to which spacing performed better for the ductility ratio parameter for the expected Yield Mode II cyclic tests can not be made. The results suggest that the ductility ratio parameter is not affected by spacing.

4.6.2 Expected Yield Mode III Connection Configuration

Figures 4.18 through 4.24 plot seven parameters and means for the five spacings tested using the expected Yield Mode III connection configuration. Tables 4.21 through 4.26 provide the results for the Tukey tests which determines whether the null hypothesis can be rejected or not for the seven parameters. Tukey tests were not performed when the ANOVA test determined that the null hypothesis could not be rejected indicating that a statistical difference in the means is not present. Appendix C provides the calculations for the ANOVA and Tukey tests.

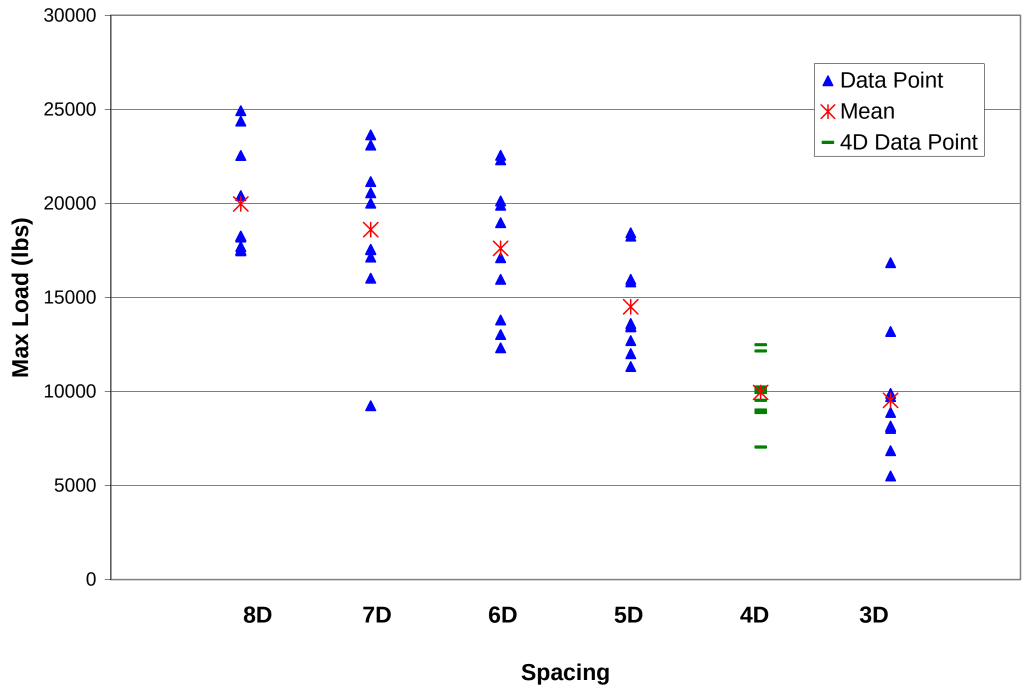

Figure 4.18: Maximum Loads and Means for Expected Yield Mode III Cyclic Tests with Data from Anderson (2002) for 4D Spacing.

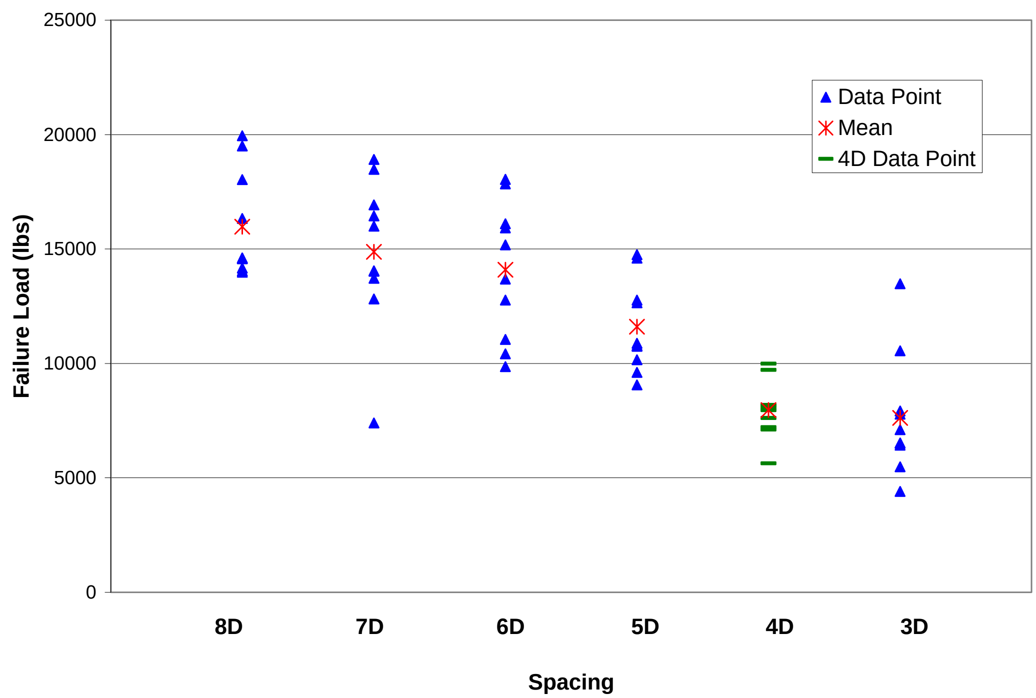

Figure 4.19: Failure Loads and Means for Expected Yield Mode III Cyclic Tests with Data from Anderson (2002) for 4D Spacing.

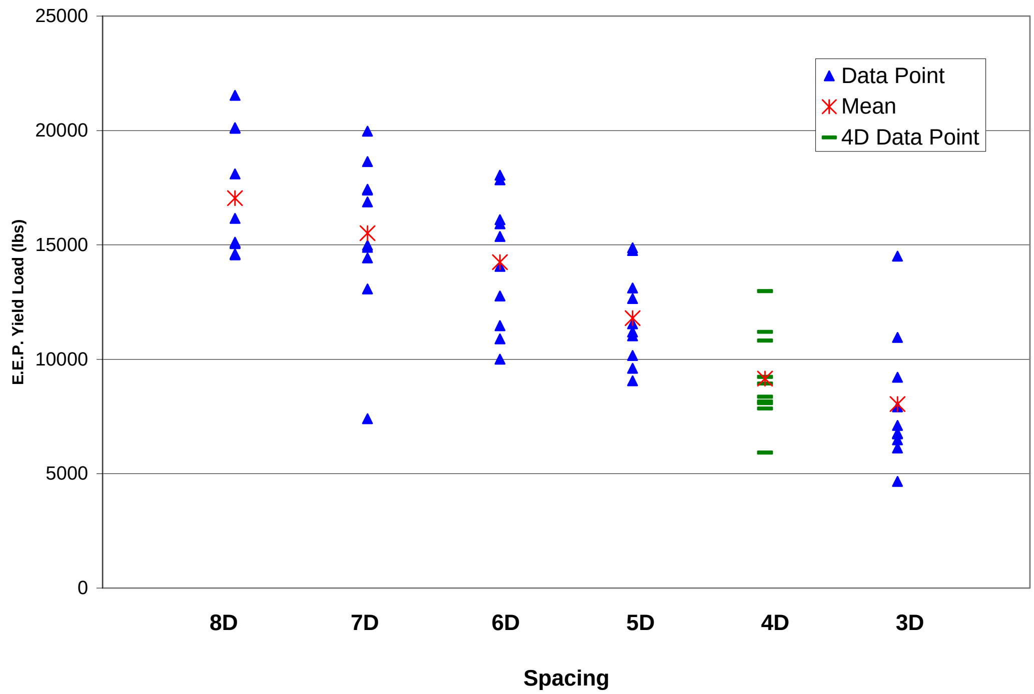

Figure 4.20: E.E.P. Yield Loads and Means for Expected Yield Mode III Cyclic Tests with Data from Anderson (2002) for 4D Spacing.

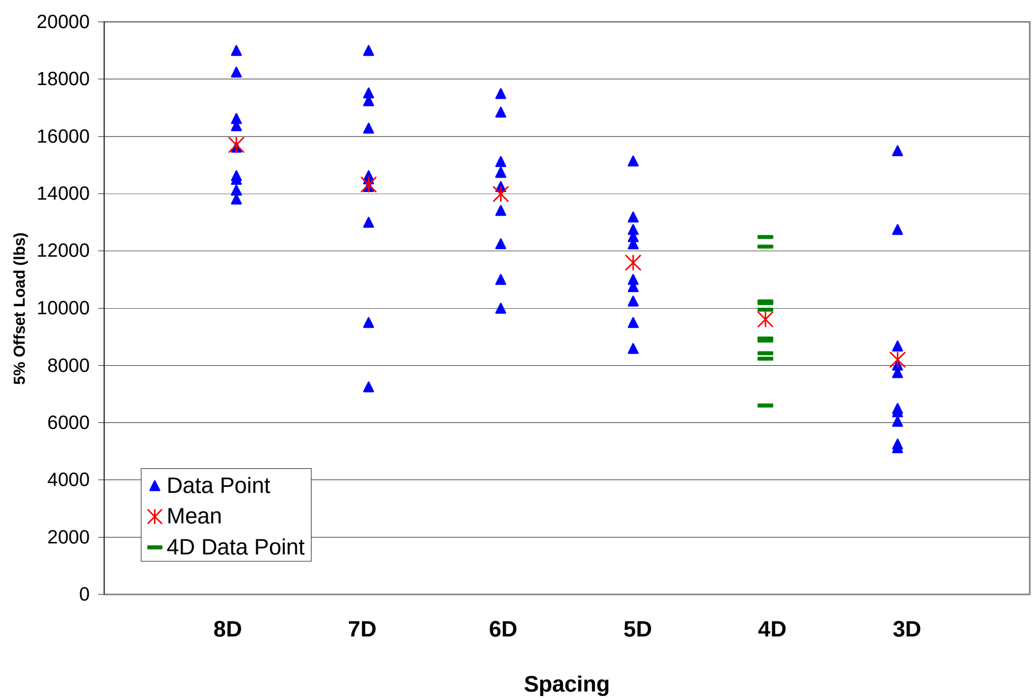

Figure 4.21: 5% Offset Loads and Means for Expected Yield Mode III Cyclic Tests with Data from Anderson (2002) for 4D Spacing.

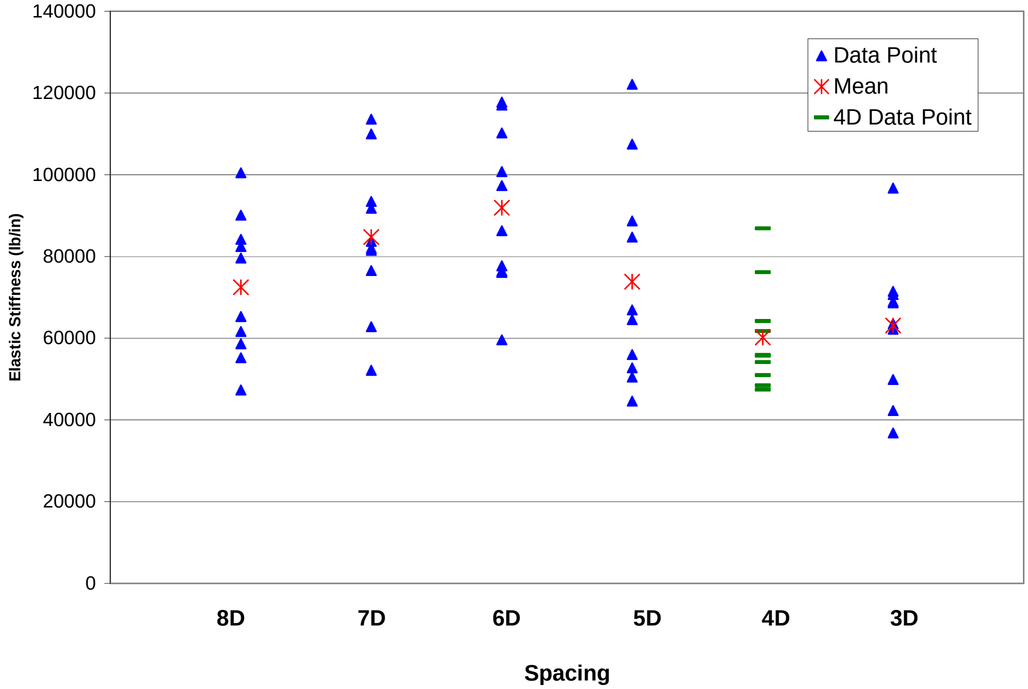

Figure 4.22: Elastic Stiffness and Means for Expected Yield Mode II Cyclic Tests with Data from Anderson (2002) for 4D Spacing.

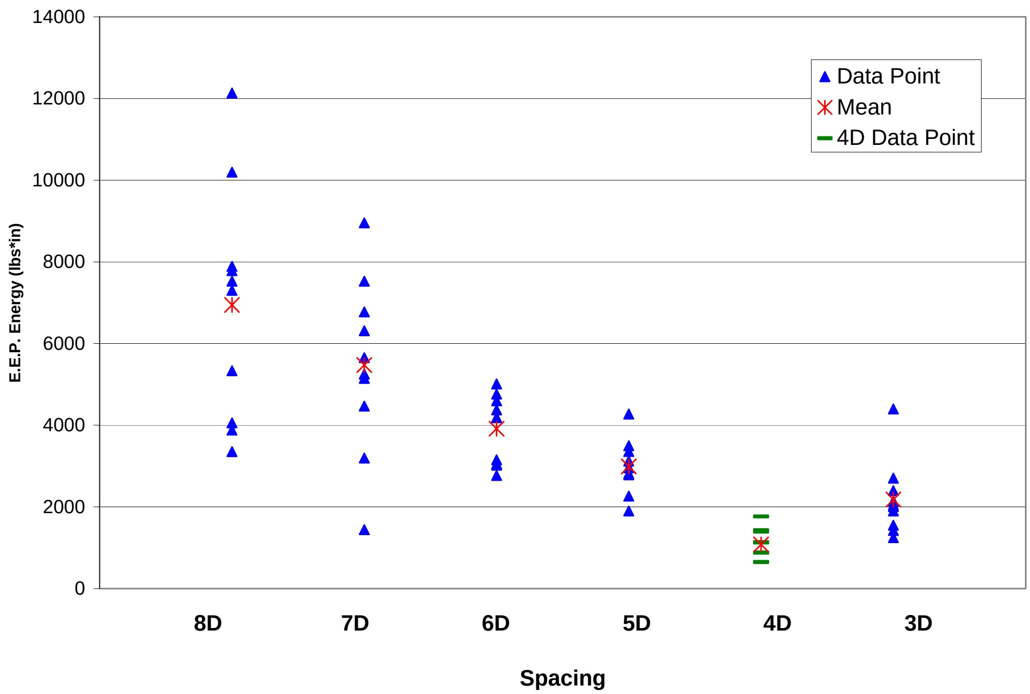

Figure 4.23: E.E.P. Energy and Means for Expected Yield Mode III Cyclic Tests with Data from Anderson (2002) for 4D Spacing.

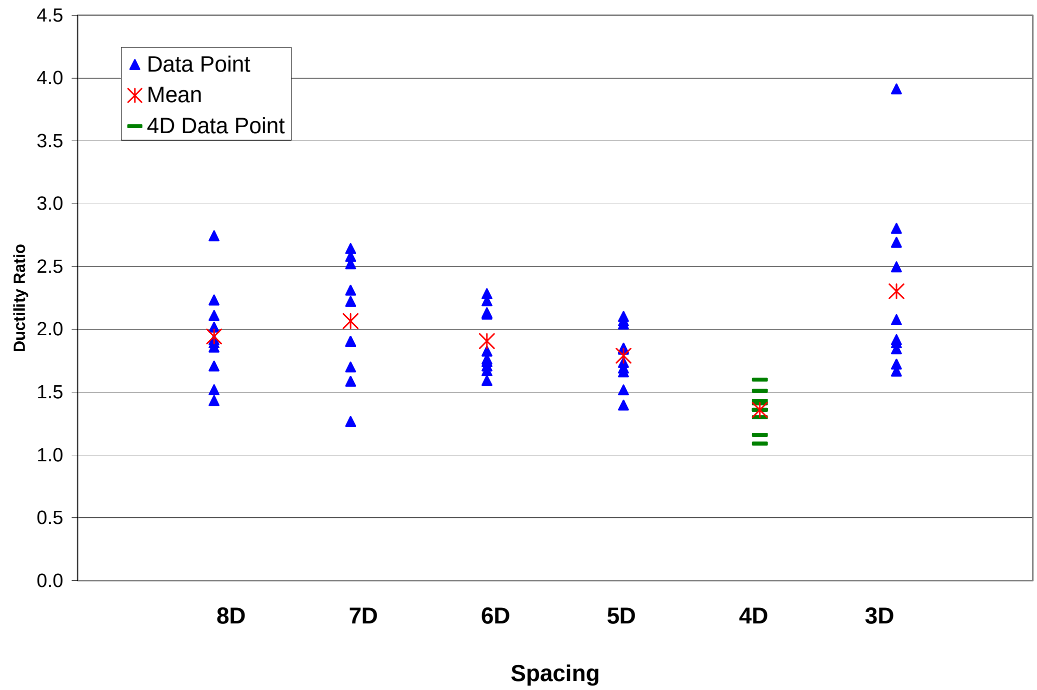

Figure 4.24: Ductility Ratio and Means for Expected Yield Mode III Cyclic Tests with Data from Anderson (2002) for 4D Spacing.

Table 4.21: Tukey Results for Maximum Load for Expected Yield Mode III Cyclic Tests.

Max Load	8D	7D	6D	5D	3D
8D	0	0	0	0	0
7D	C.R. Ho	0	0	0	0
6D	C.R. Ho	C.R. Ho	0	0	0
5D	Reject Ho	C.R. Ho	C.R. Ho	0	0
3D	Reject Ho	Reject Ho	Reject Ho	Reject Ho	0

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.22: Tukey Results for Failure Load for Expected Yield Mode III Cyclic Tests.

Failure Load	8D	7D	6D	5D	3D
8D	0				
7D	C.R. Ho	0			
6D	C.R. Ho	C.R. Ho	0		
5D	Reject Ho	C.R. Ho	C.R. Ho	0	
3D	Reject Ho	Reject Ho	Reject Ho	Reject Ho	0

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.23: Tukey Results for E.E.P. Yield Load for Expected Yield Mode III Cyclic Tests.

Yield Load	8D	7D	6D	5D	3D
8D	0				
7D	C.R. Ho	0			
6D	C.R. Ho	C.R. Ho	0		
5D	Reject Ho	Reject Ho	C.R. Ho	0	
3D	Reject Ho	Reject Ho	Reject Ho	Reject Ho	0

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.24: Tukey Results for 5% Offset Load for Expected Yield Mode III Cyclic Tests.

5% Offset Load	8D	7D	6D	5D	3D
8D	0	0	0	0	0
7D	C.R. Ho	0	0	0	0
6D	C.R. Ho	C.R. Ho	0	0	0
5D	Reject Ho	C.R. Ho	C.R. Ho	0	0
3D	Reject Ho	Reject Ho	Reject Ho	C.R. Ho	0

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.25: Tukey Results for Elastic Stiffness for Expected Yield Mode III Cyclic Tests.

Elastic Stiffness	8D	7D	6D	5D	3D
8D	0				
7D	C.R. Ho	0			
6D	C.R. Ho	C.R. Ho	0		
5D	C.R. Ho	C.R. Ho	C.R. Ho	0	
3D	C.R. Ho	C.R. Ho	Reject Ho	C.R. Ho	0

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.26: Tukey Results for E.E.P. Energy for Expected Yield Mode III Cyclic Tests.

E.E.P. Energy	8D	7D	6D	5D	3D
8D	0				
7D	C.R. Ho	0			
6D	Reject Ho	C.R. Ho	0		
5D	Reject Ho	Reject Ho	C.R. Ho	0	
3D	Reject Ho	Reject Ho	C.R. Ho	C.R. Ho	0

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

The null hypothesis could not be rejected for five of the compared means for the maximum load parameter; the 8D spacing compared to 7D, 8D spacing compared to 6D, 7D spacing compared to 5D, 6D spacing compared to 5D, and 7D compared to 6D as indicated in Table 4.21. From Figure 4.18 it can be seen that the means for the 8D, 7D, and 6D spacing are similar while the results for the 5D and 3D spacings are less. Therefore, the 8D, 7D, and 6D spacing are more optimal than the 5D and 3D spacing since the larger spacings resulted in larger mean values. Among the 8D, 7D, and 6D spacings, the 6D spacing is concluded to be the most optimum for the maximum load parameter for the expected Yield Mode III cyclic tests because smaller spacings are more economic.

For the failure load parameter, the null hypothesis can not be rejected for 8D spacing compared to 7D, 8D compared to 6D, 7D compared 6D, 7D compared to 5D, and 6D compared to 5D as indicated by Table 4.22. No determination can be made for optimal spacing for the failure load parameter for the expected Yield Mode III cyclic tests.

The null hypothesis can not be rejected for four mean comparisons for E.E.P. yield load parameter; 8D compared to 7D, 8D compared to 6D, 7D compared to 6D, and 6D spacing compared to 5D as indicated in Table 4.23. From Figure 4.20 it can be seen that the means for the 8D, 7D, and 6D spacing are similar while the results for the 5D and 3D spacings are less. Therefore, the 8D, 7D, and 6D spacing are more optimal than the 5D and 3D spacing since the larger spacings resulted in larger mean values. Among the 8D, 7D, and 6D spacings, the 6D spacing is concluded to be the most optimum for the E.E.P. yield load parameter for the expected Yield Mode III cyclic tests because smaller spacings are more economic.

The null hypothesis can not be rejected for six mean comparisons for the 5% offset load parameter; 8D compared to 7D, 8D compared to 6D, 7D compared to 6D, 7D spacing compared to 5D, 6D spacing compared to 5D, and 5D spacing compared to 3D as indicated in Table 4.24. From Figure 4.21 it can be seen that the means for the 8D, 7D, and 6D spacing are similar while the results for the 5D and 3D spacings are less. Therefore, the 8D, 7D, and 6D spacing are more optimal than the 5D and 3D spacing since the larger spacings resulted in larger mean values. Among the 8D, 7D, and 6D spacings, the 6D spacing is concluded to be the most optimum for the 5% offset load parameter for the expected Yield Mode III cyclic tests because smaller spacings are more economic.

One of the compared means for elastic stiffness was determined to be statistically different; 6D compared to 3D as indicated in Table 4.25. No determination can be made for optimal spacing for the elastic stiffness parameter for the expected Yield Mode III cyclic tests. The results suggest that the elastic stiffness parameter is not affected by spacing but rather it is a function of the fastener bearing on the wood material only.

For E.E.P. energy, the null hypothesis could not be rejected for five means; 8D compared to 7D, 7D compared to 6D, 6D compared to 5D, 6D compared to 3D, and 5D compared to 3D as indicated in Table 4.26. From Figure 4.23 it can be seen that the means for the 8D and 7D spacing are similar while the results for the 6D, 5D, and 3D spacings are less. Therefore, the 8D and 7D spacings are more optimal than the 6D, 5D, and 3D spacing since the larger spacings resulted in larger mean values. Between the 8D and 7D spacings, the 7D spacing is concluded to be the most optimum for the E.E.P. energy parameter for the expected Yield Mode III cyclic tests because smaller spacings are more economic.

The results for the ANOVA test for the ductility ratio parameter showed that the null hypothesis can not be rejected for any of the mean comparisons. Therefore, the Tukey test was not performed on the multiple comparisons. The results suggest that the ductility ratio parameter is not affected by spacing.

4.6.3 Expected Yield Mode IV Connection Configuration

Figure 4.25 through 4.31 plot the mean of seven parameters for the five spacings tested using the Expected Yield Mode IV connection configuration. Tables 4.27 through 4.32 provide the results for the Tukey tests which determines whether the null hypothesis can be rejected or not for the seven parameters. Tukey tests were not performed when the ANOVA test determined that the null hypothesis could not be rejected indicating that a statistical difference in the means is not present. Appendix C provides the calculations for the ANOVA and Tukey tests.

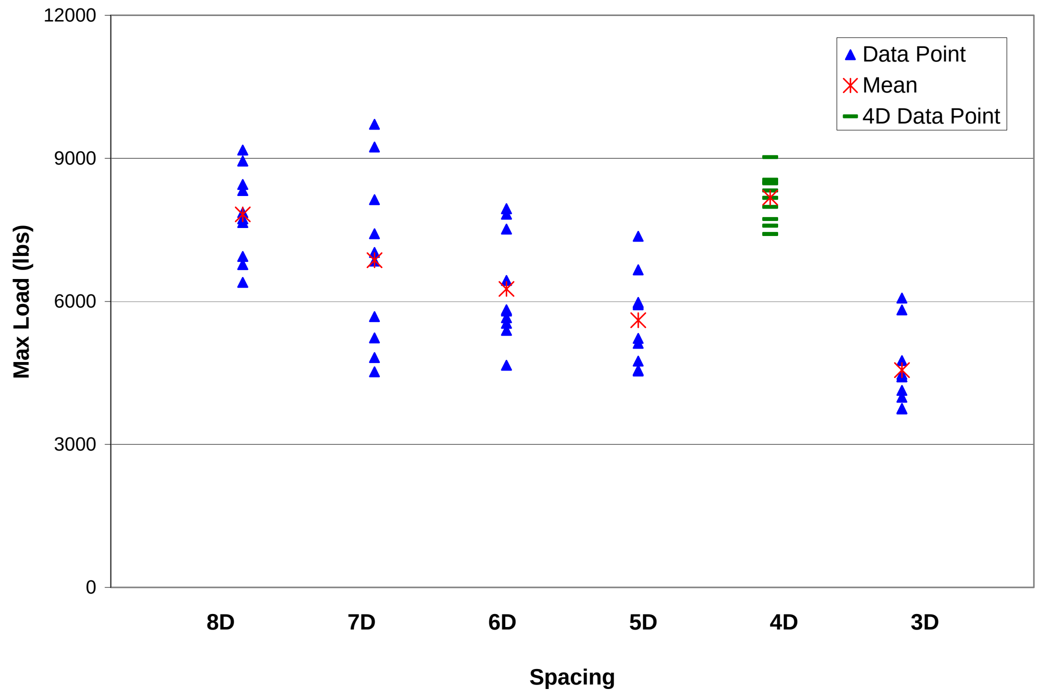

Figure 4.25: Maximum Loads and Means for Expected Yield Mode IV Cyclic Tests with Data from Anderson (2002) for 4D Spacing.

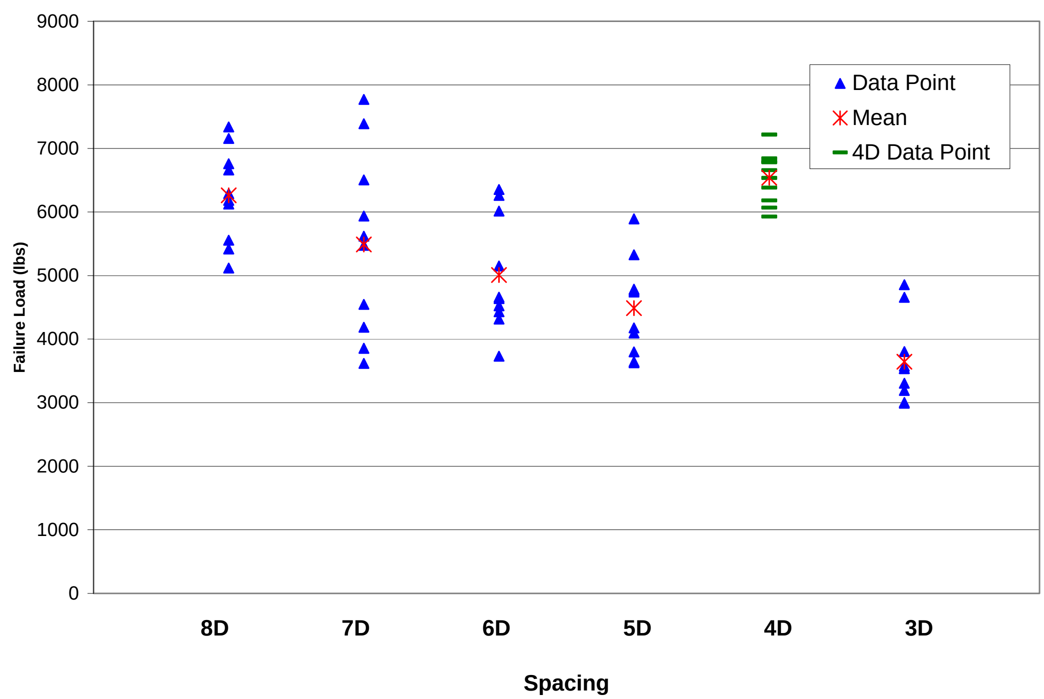

Figure 4.26: Failure Loads and Means for Expected Yield Mode IV Cyclic Tests with Data from Anderson (2002) for 4D Spacing.

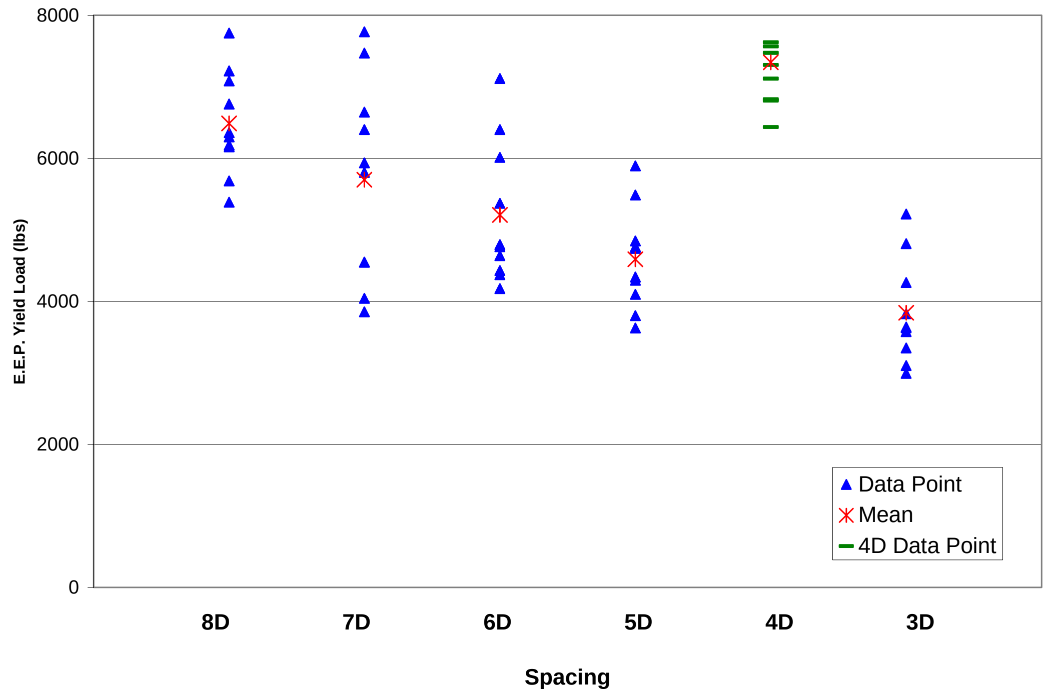

Figure 4.27: E.E.P. Yield Loads and Means for Expected Yield Mode IV Cyclic Tests with Data from Anderson (2002) for 4D Spacing.

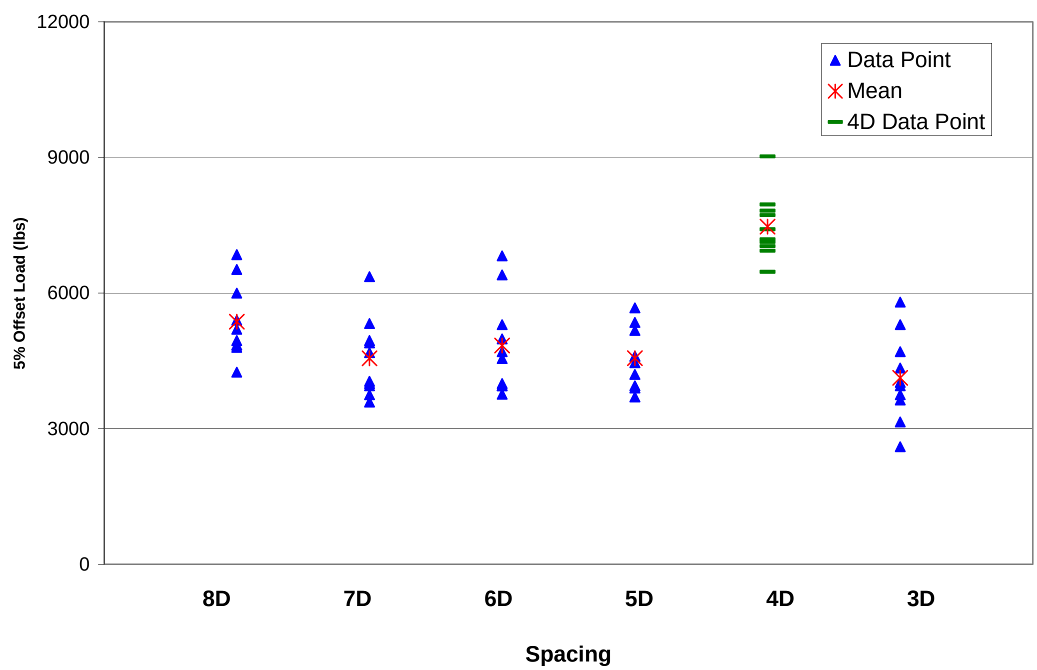

Figure 4.28: 5% Offset Loads and Means for Expected Yield Mode IV Cyclic Tests with Data from Anderson (2002) for 4D Spacing.

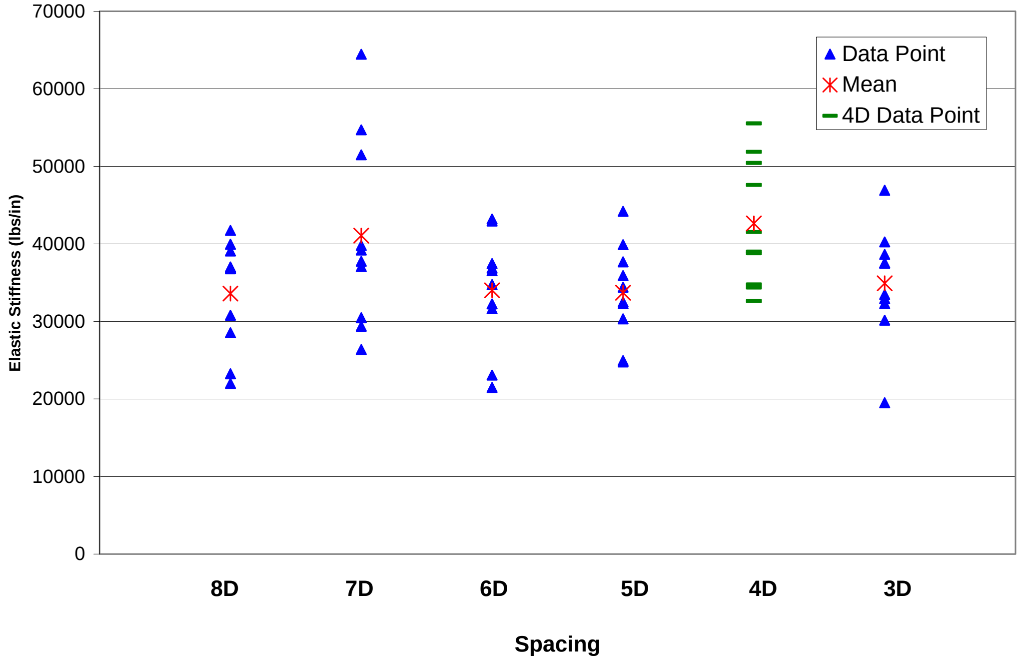

Figure 4.29: Elastic Stiffness and Means for Expected Yield Mode IV Cyclic Tests with Data from Anderson (2002) for 4D Spacing.

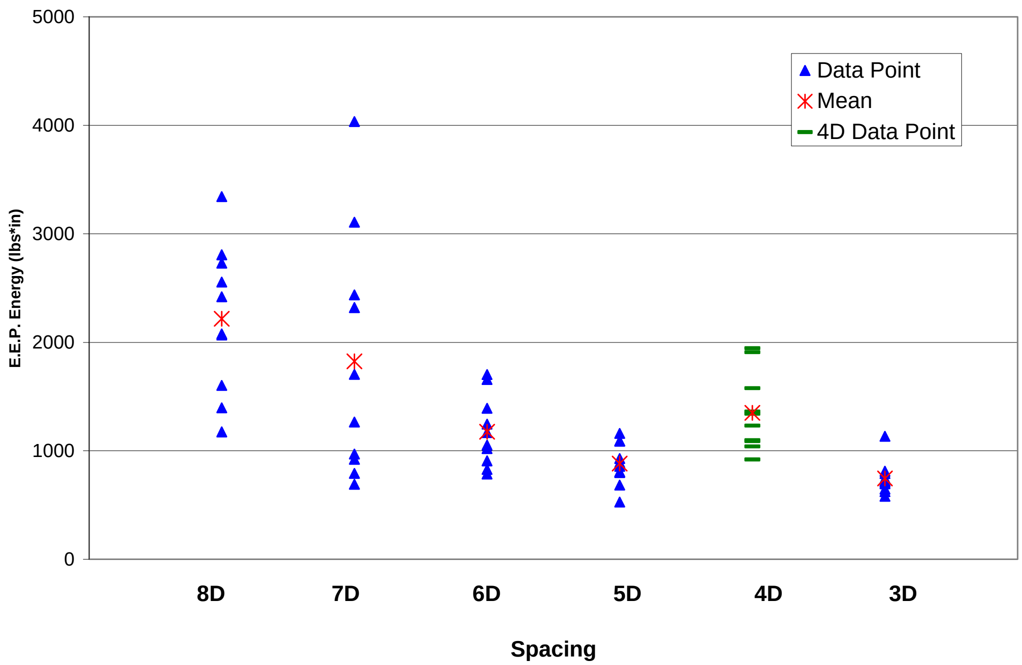

Figure 4.30: E.E.P. Energy and Means for Expected Yield Mode IV Cyclic Tests with Data from Anderson (2002) for 4D Spacing.

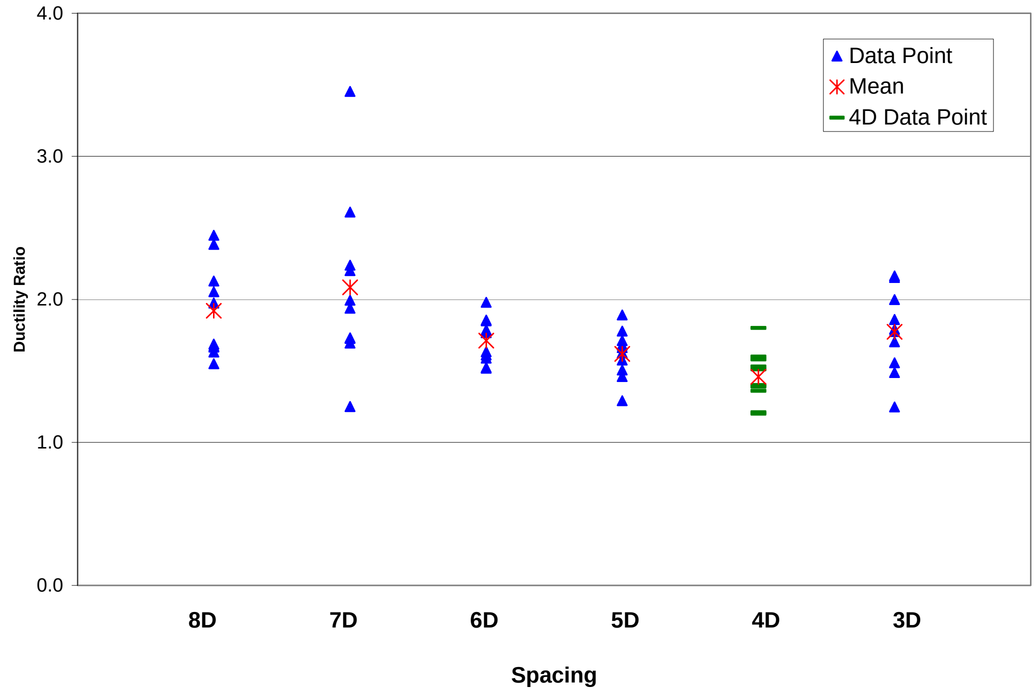

Figure 4.31: Ductility Ratio and Means for Expected Yield Mode IV Cyclic Tests with Data from Anderson (2002) for 4D Spacing.

Table 4.27: Tukey Results for Maximum Load for Expected Yield Mode IV Cyclic Tests.

Max Load	8D	7D	6D	5D	3D
8D	0	0	0	0	0
7D	C.R. Ho	0	0	0	0
6D	Reject Ho	C.R. Ho	0	0	0
5D	Reject Ho	C.R. Ho	C.R. Ho	0	0
3D	Reject Ho	Reject Ho	Reject Ho	C.R. Ho	0

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.28: Tukey Results for Failure Load for Expected Yield Mode IV Cyclic Tests.

Failure Load	8D	7D	6D	5D	3D
8D	0				
7D	C.R. Ho	0			
6D	Reject Ho	C.R. Ho	0		
5D	Reject Ho	C.R. Ho	C.R. Ho	0	
3D	Reject Ho	Reject Ho	Reject Ho	C.R. Ho	0

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.29: Tukey Results for E.E.P. Yield Load for Expected Yield Mode IV Cyclic Tests.

Yield Load	8D	7D	6D	5D	3D
8D	0				
7D	C.R. Ho	0			
6D	Reject Ho	C.R. Ho	0		
5D	Reject Ho	C.R. Ho	C.R. Ho	0	
3D	Reject Ho	Reject Ho	Reject Ho	C.R. Ho	0

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.30: Tukey Results for 5% Offset Load for Expected Yield Mode IV Cyclic Tests.

5% Offset Load	8D	7D	6D	5D	3D
8D	0				
7D	C.R. Ho	0			
6D	C.R. Ho	C.R. Ho	0		
5D	C.R. Ho	C.R. Ho	C.R. Ho	0	
3D	Reject Ho	Reject Ho	C.R. Ho	C.R. Ho	0

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.31: Tukey Results for E.E.P. Energy for Expected Yield Mode IV Cyclic Tests.

E.E.P. Energy	8D	7D	6D	5D	3D
8D	0				
7D	C.R. Ho	0			
6D	Reject Ho	C.R. Ho	0		
5D	Reject Ho	Reject Ho	C.R. Ho	0	
3D	Reject Ho	Reject Ho	C.R. Ho	C.R. Ho	0

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.32: Tukey Results for Ductility Ratio for Expected Yield Mode IV Cyclic Tests.

Ductility Ratio	8D	7D	6D	5D	3D
8D	0				
7D	C.R. Ho	0			
6D	C.R. Ho	C.R. Ho	0		
5D	C.R. Ho	Reject Ho	C.R. Ho	0	
3D	C.R. Ho	C.R. Ho	C.R. Ho	C.R. Ho	0

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

As indicated in Table 4.27, the null hypothesis could not be rejected for five means for the maximum load parameter; 8D compared to 7D, 7D compared to 6D, 7D compared to 5D, 6D compared to 5D, and 5D compared to 3D. No determination can be made for the optimal spacing for the maximum load parameter for expected Yield Mode IV cyclic tests. The visual trends seen in Figure 4.25 indicate that the 8D spacing provided higher values; however, the large variation in the 7D results may be causing the Tukey tests to consider no statistical difference between the two spacings.

As indicated in Table 4.28, the null hypothesis for the failure load parameter could not be rejected for five of the compared means: 8D compared to 7D, 7D compared to 6D, 7D compared to 5D, 6D compared to 5D, and 5D compared to 3D. A clear determination as to which spacing performed better for the failure load parameter for the expected Yield Mode IV cyclic tests can not be made. The visual trends seen in Figure 4.26 indicate that the 8D spacing provided higher values; however, the large variation in the 7D results may be causing the Tukey tests to consider no statistical difference between the two spacings.

The null hypothesis that the means are statistically the same could not be rejected for five comparisons for the E.E.P. yield load parameter; 8D compared to 7D, 7D compared to 6D, 7D compared to 5D, 6D compared to 5D, and 5D compared to 3D as indicated in Table 4.29. From Figure 4.27 it can be seen that the means for the 8D and 7D spacing are similar while the results for the 6D, 5D, and 3D spacings are less. Therefore, the 8D and 7D spacings are more optimal than the 6D, 5D, and 3D spacing since the larger spacings resulted in larger mean values. Between the 8D and 7D spacings, the 7D spacing is concluded to be the most optimum for the E.E.P. yield load parameter for the expected Yield Mode IV cyclic tests because smaller spacings are more economic. The visual trends seen in Figure 4.27 indicate that the 8D spacing provided higher values; however, the large variation in the other spacings may be causing the Tukey tests to consider that no statistical difference exists.

Two means were determined to be statistically different for the 5% offset load parameter; 8D compared to 3D, 7D compared to 3D as indicated in Table 4.30. A clear determination as to which spacing performed better for the 5% offset load parameter for the expected Yield Mode IV cyclic tests can not be made.

The results for the ANOVA test for the elastic stiffness parameter showed that the null hypothesis can not be rejected for any of the mean comparisons. Therefore, the Tukey test was not performed on the multiple comparisons. A clear determination as to which spacing performed better for the elastic stiffness parameter for the expected Yield Mode IV cyclic tests can not be made indicating that the elastic stiffness parameter is not influenced by the spacing between bolts.

Results for the E.E.P. energy parameter showed that the null hypothesis could not be rejected for five mean comparisons; 8D compared to 7D, 7D compared to 6D, 6D compared to 5D, 6D compared to 3D, and 5D compared to 3D. From Figure 4.30 it can be seen that the means for the 8D and 7D spacing are similar while the results for the 6D, 5D, and 3D spacings are less. Therefore, the 8D and 7D spacings are more optimal than the 6D, 5D, and 3D spacing since the larger spacings resulted in larger mean values. Between the 8D and 7D spacings, the 7D spacing is concluded to be the most optimum for the E.E.P. energy parameter for the expected Yield Mode IV cyclic tests because smaller spacings are more economic.

As indicated by Table 4.32, only one mean comparison for the ductility ratio could be rejected: 7D compared to 5D. A clear determination as to which spacing performed better for the ductility ratio parameter for the expected Yield Mode IV cyclic tests can not be made. The results suggest that the ductility ratio parameter is not affected by spacing.

4.7 Comparison of Results with Previous Research on 4D spacing

Results from this research can be compared to those from research performed by Anderson (2002). Anderson tested timber connections under cyclic loading for three yield modes using the NDS recommended spacing of 4D and published results for various parameters. He tested various numbers of bolts and multiple rows of bolts. To compare results, Anderson's tests that used five bolts in a single row were examined. To test expected Yield Mode II, he joined two 2x6 pieces of Southern Yellow Pine lumber with five 1/2 in. bolts and tested until failure. To test expected Yield Mode III, he joined one 4x6 piece of Southern Yellow Pine lumber and a 0.25 in. steel plate with five 3/8 in bolts. To test expected Yield Mode IV, he joined two 4x6 pieces of Southern Pine lumber with five 3/8 in bolts. The tests performed by Anderson did not behave as the yield model predicted, but exhibited signs of mixed yielding modes. Further discussion on results from Anderson's tests can be found in the predicted yield mode discussion section.

To make inferences whether the 4D spacing between bolts is statistically different from other spacings in terms of strength and serviceability parameters, statistical analysis was performed on the tests that underwent reverse cyclic loading. It was assumed that the data is normally distributed and the standard deviations are equal. A significance level of α=0.05 was used to test the null hypothesis, H_o, that any two means are equal. The analysis of variance (ANOVA) was used to compare data and determine whether the means for several parameters for each connection layout are statistically different. See Chapter 3 for description of parameters and how they are determined. For example, the results for 8D, 7D, 6D, 5D, and 3D spacing for the expected Yield Mode II connection configuration for the maximum load parameter were compared with results for the 4D spacing. The F value was compared to the $F_{critical}$ value. If F is larger than $F_{critical}$ than there is a statistical difference between the means and the null hypothesis is rejected for the group of spacings. Further testing is then needed to determine which spacings are different. If F is smaller than $F_{critical}$ than there is not a statistical difference between the means and the null hypothesis can not be rejected. Further testing among the spacings is not required.

Tables 4.33 through 4.53 provide the results for the Tukey tests which determines whether the null hypothesis can be rejected or not for the seven parameters. Tukey tests were not performed when the ANOVA test determined that the null hypothesis could not be rejected indicating that a statistical difference in the means is not present. Appendix C provides the calculations for the ANOVA and Tukey tests.

4.7.1 Expected Yield Mode II

Table 4.33: Tukey Results for Maximum Load for Expected Yield Mode II Cyclic Tests.

Max Load	8D	7D	6D	5D	3D
4D	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.34: Tukey Results for Failure Load for Expected Yield Mode II Cyclic Tests.

Failure Load	8D	7D	6D	5D	3D
4D	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.35: Tukey Results for E.E.P. Yield Load for Expected Yield Mode II Cyclic Tests.

Yield Load	8D	7D	6D	5D	3D
4D	Reject Ho	Reject Ho	Reject Ho	Reject Ho	C.R. Ho

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.36: Tukey Results for 5% Offset Load for Expected Yield Mode II Cyclic Tests.

5% Offset Load	8D	7D	6D	5D	3D
4D	Reject Ho	Reject Ho	Reject Ho	Reject Ho	C.R. Ho

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.37: Tukey Results for Elastic Stiffness for Expected Yield Mode II Cyclic Tests.

Elastic Stiffness	8D	7D	6D	5D	3D
4D	Reject Ho	Reject Ho	Reject Ho	C.R. Ho	Reject Ho

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.38: Tukey Results for E.E.P. Energy for Expected Yield Mode II Cyclic Tests.

E.E.P. Energy	8D	7D	6D	5D	3D
4D	Reject Ho	Reject Ho	Reject Ho	C.R. Ho	C.R. Ho

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.39: Tukey Results for Ductility Ratio for Expected Yield Mode II Cyclic Tests.

Ductility Ratio	8D	7D	6D	5D	3D
4D	Reject Ho	Reject Ho	Reject Ho	C.R. Ho	Reject Ho

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

For two parameters all but one of the compared means was determined to be statistically different. The null hypothesis could not be rejected for 4D compared to 3D for E.E.P. yield load and 5% offset load parameters. Therefore, the results show that the larger spacings (5D, 6D, 7D, and 8D) are more optimal than the 4D spacing because larger values were obtained.

The results for the ANOVA test for the failure load parameter showed that the null hypothesis can not be rejected for any of the mean comparisons. Therefore, the Tukey test was not performed on the multiple comparisons. A clear determination as to which spacing performed better for the failure load parameter for the expected Yield Mode II cyclic tests can not be made. The results suggest that the failure load parameter is not affected by spacing.

One of the compared means was determined to be statistically different for the elastic stiffness and ductility ratio parameters. The null hypothesis could not be rejected for 4D compared to 5D. Therefore, the results show that the larger spacings (6D, 7D, and 8D) are more optimal than the 4D spacing because larger values were obtained.

Two of the compared means was determined to be statistically different for the E.E.P. energy parameter. The null hypothesis could not be rejected for 4D compared to 5D and 4D compared to 3D. Therefore, the results show that the larger spacings (6D, 7D, and 8D) are more optimal than the 4D spacing because larger values were obtained.

The null hypothesis was rejected for all mean comparisons for the maximum load parameter. Therefore, the results show that the larger spacings (5D, 6D, 7D, and 8D) are more optimal than the 4D spacing because larger values were obtained.

4.7.2 Expected Yield Mode III

Table 4.40: Tukey Results for Maximum Load for Expected Yield Mode III Cyclic Tests.

Max Load	8D	7D	6D	5D	3D
4D	Reject Ho	Reject Ho	Reject Ho	Reject Ho	C.R. Ho

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.41: Tukey Results for Failure Load for Expected Yield Mode III Cyclic Tests.

Failure Load	8D	7D	6D	5D	3D
4D	Reject Ho	Reject Ho	Reject Ho	Reject Ho	C.R. Ho

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.42: Tukey Results for E.E.P. Yield Load for Expected Yield Mode III Cyclic Tests.

Yield Load	8D	7D	6D	5D	3D
4D	Reject Ho	Reject Ho	Reject Ho	C.R. Ho	C.R. Ho

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.43: Tukey Results for 5% Offset Load for Expected Yield Mode III Cyclic Tests.

5% Offset Load	8D	7D	6D	5D	3D
4D	Reject Ho	Reject Ho	Reject Ho	C.R. Ho	C.R. Ho

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.44: Tukey Results for Elastic Stiffness for Expected Yield Mode III Cyclic Tests.

Elastic Stiffness	8D	7D	6D	5D	3D
4D	C.R. Ho	C.R. Ho	Reject Ho	C.R. Ho	C.R. Ho

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.45: Tukey Results for E.E.P. Energy for Expected Yield Mode III Cyclic Tests.

E.E.P. Energy	8D	7D	6D	5D	3D
4D	Reject Ho	Reject Ho	Reject Ho	C.R. Ho	C.R. Ho

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.46: Tukey Results for Ductility Ratio for Expected Yield Mode III Cyclic Tests.

Ductility Ratio	8D	7D	6D	5D	3D
4D	Reject Ho	Reject Ho	Reject Ho	C.R. Ho	Reject Ho

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

For two of the seven parameters examined, the null hypothesis was rejected for all but one of mean comparisons; 4D compared to 3D. Therefore, the results for the maximum load and failure load parameters for expected Yield Mode III cyclic tests show that the larger spacings (5D, 6D, 7D, and 8D) are more optimal than the 4D spacing because larger values for the larger spacings were obtained.

For three of the seven parameters, the null hypothesis could not be rejected for two mean comparisons. For E.E.P. yield load, 5% offset load parameters, and E.E.P. energy; the null hypothesis could not be rejected for the 4D spacing compared to the 3D spacing and 4D compared to 5D. Therefore, results for the E.E.P. yield load, 5% offset load, and E.E.P. energy parameters for the expected Yield Mode III cyclic tests show that the larger spacings (6D, 7D, 8D) are more optimal than 4D larger values for the larger spacings were obtained.

For the elastic stiffness parameter, the null hypothesis could not be rejected for four of the mean comparisons; 4D compared to 8D, 4D compared to 7D, 4D compared to 5D, and 4D compared to 3D. A clear determination as to which spacing performed better for the elastic stiffness parameter for the expected Yield Mode III cyclic tests can not be made. The results suggest that the failure load parameter is not affected by spacing.

For the ductility ratio parameter, the null hypothesis could not be rejected for one of the mean comparisons; 4D compared to 5D. Therefore, the results for ductility ratio parameter for expected Yield Mode III cyclic tests show that the larger spacings (7D, 8D, 6D) are more optimal than the 4D spacing because larger values for the larger spacings were obtained.

4.7.3 Expected Yield Mode IV

Table 4.47: Tukey Results for Maximum Load for Expected Yield Mode IV Cyclic Tests.

Max Load	8D	7D	6D	5D	3D
4D	C.R. Ho	C.R. Ho	Reject Ho	Reject Ho	Reject Ho

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.48: Tukey Results for Failure Load for Expected Yield Mode IV Cyclic Tests.

Failure Load	8D	7D	6D	5D	3D
4D	C.R. Ho	C.R. Ho	Reject Ho	Reject Ho	Reject Ho

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.49: Tukey Results for E.E.P. Yield Load for Expected Yield Mode IV Cyclic Tests.

Yield Load	8D	7D	6D	5D	3D
4D	C.R. Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.50: Tukey Results for 5% Offset Load for Expected Yield Mode IV Cyclic Tests.

5% Offset Load	8D	7D	6D	5D	3D
4D	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.51: Tukey Results for Elastic Stiffness for Expected Yield Mode IV Cyclic Tests.

Elastic Stiffness	8D	7D	6D	5D	3D
4D	C.R. Ho	C.R. Ho	C.R. Ho	C.R. Ho	C.R. Ho

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.52: Tukey Results for E.E.P. Energy for Expected Yield Mode IV Cyclic Tests.

E.E.P. Energy	8D	7D	6D	5D	3D
4D	Reject Ho	C.R. Ho	C.R. Ho	C.R. Ho	C.R. Ho

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

Table 4.53: Tukey Results for Ductility Ratio for Expected Yield Mode IV Cyclic Tests.

Ductility Ratio	8D	7D	6D	5D	3D
4D	Reject Ho	Reject Ho	C.R. Ho	C.R. Ho	C.R. Ho

Reject Ho: Reject null hypothesis that means are equal

C.R. Ho: Can not reject null hypothesis that means are equal

The null hypothesis can not be rejected for two of the compared means for the maximum load parameter; 4D compared to 8D and 4D compared to 7D. Results do not show that the larger spacings are more optimal than the 4D spacing for the maximum load parameter for the expected Yield Mode IV cyclic tests.

The results for the ANOVA test for the failure load parameter showed that the null hypothesis can not be rejected for any of the mean comparisons. Therefore, the Tukey test was not performed on the multiple comparisons. A clear determination as to which spacing performed better for the failure load parameter for the expected Yield Mode IV cyclic tests can not be made. The results suggest that the failure load parameter is not affected by spacing.

The null hypothesis could not be rejected for one of the mean comparisons for the E.E.P. yield load parameter; 4D compared to 8D. Results do not show that the larger spacings are more optimal than the 4D spacing for the E.E.P. yield load parameter for the expected Yield Mode IV cyclic tests.

For 5% offset load parameter, the null hypothesis was rejected for all mean comparisons. Therefore, the results for the 5% offset for the expected Yield Mode IV cyclic tests show that the larger spacings (5D, 6D, 7D, and 8D) are more optimum than the 4D spacing because larger values for the larger spacings were obtained.

The null hypothesis could not be rejected for all the mean comparisons for the elastic stiffness parameter. A clear determination as to which spacing performed better for the elastic stiffness parameter for the expected Yield Mode IV cyclic tests can not be made. The results suggest that the elastic stiffness parameter is not affected by spacing.

The null hypothesis was rejected for one mean comparison for the E.E.P. energy parameter; 4D compared to 8D. Results do not show that the larger spacings are more optimal than the 4D spacing for the E.E.P. energy parameter for the expected Yield Mode IV cyclic tests.

The null hypothesis can not be rejected for tthree of the compared means for the ductility ratio parameter; 4D compared to 6D, 4D compared to 5D, and 4D compared to 3D. Therefore, the results for the ductility ratio for the expected Yield Mode IV cyclic tests show that the larger spacings (7D and 8D) are more optimum than the 4D spacing because larger values for the larger spacings were obtained.

4.8 Predicted Yield Mode Discussion

At the beginning of this research several assumptions were made in the calculation of yield modes. The yield strength of the bolts was taken as 45,000 psi as recommended by NDS. The specific gravity of the wood was taken from tables provided by NDS as 0.55 for Southern Yellow Pine and 0.51 for Mixed Southern Yellow Pine. The 4x6 material used in the expected Yield Mode III connection tests was graded as Mixed Southern Yellow Pine. All other wood was graded as Southern Yellow Pine. NDS states that the dowel embedment strength of the wood can be calculated and is equal to 11,200 * G where G is specific gravity. With the assumed values of specific gravity and yield strength of the bolts, the calculation of the expected yield modes was made. This research performed tests to determine the dowel bearing strength of the wood and the yield strength of the bolts. After testing was completed, the average values of the yield strength of the bolt and the dowel bearing strength of the wood were calculated and the calculation of the yield mode was redone.

The wood material used in the expected Yield Mode II tests had an average dowel bearing strength of 4363 psi and the bolts had an average yield strength of 55,451 psi. The wood material used in the expected Yield Mode III test had an average dowel bearing strength of 4076 psi and the bolts had an average yield strength of 61,298 psi. The wood material used in the Yield Mode IV tests had an average dowel bearing strength of 5115 psi and the bolts had an average yield strength of 68,612 psi.

With the measured values of specific gravity and yield strength of the bolts, the calculation for predicted yield modes were redone. The connection layout for the expected Yield Mode II (two 2x6 lumber with 3/4 in. bolts) continues to be considered Yield Mode II. The connection layout for the expected Yield Mode III (one 4x6 lumber and one 0.25 in. steel plate with 1/2 in. bolts) is now considered Yield Mode II which is consistent with results seen in testing. The connection layout for the expected Yield Mode IV (two 2x6 with 3/8 in. bolts) also changes type of yielding to Yield Mode II which is consistent with results seen in testing. See Table 4.49 for capacity, Z, calculations of expected Yield Mode III based on measured values of dowel embedment strength and yield strength of the bolts. See Table 4.50 for capacity, Z, calculations for expected Yield Mode IV based on measured values. See Chapter 2 for description of terms and formulas.

Table 4.54: Capacity, Z, calculations for Expected Yield Mode III with Measured Values of Dowel Embedment Strength, F_{em} and F_{es}, and Yield Strength of Bolt, $F_{yb.}$

tm =	3.5	inches
ts =	0.5	inches
D =	0.5	inches
G =	0.51	
Fem =	4076	psi
Fes =	58000	psi
Fyb =	61298	psi
Rt =	7.0	
Re =	0.1	
k1 =	0.23	
k2 =	0.5	
k3 =	6.2	
θ =	0	
Kθ =	1	
ZIm =	1783	
ZIs =	3625	
ZII =	**919**	
ZIIIm =	1057	
ZIIIs =	947	
ZIV =	975	

Table 4.55: Z calculations for Expected Yield Mode IV with Measured Values of Dowel Embedment Strength, F_{em} and F_{es}, and Yield Strength of Bolt, $F_{yb.}$

tm =	1.5	inches
ts =	1.5	inches
D =	0.375	inches
G =	0.55	
Fem =	5115	psi
Fes =	5115	psi
Fyb =	68612	psi
Rt =	1	
Re =	1.0	
k1 =	0.41	
k2 =	1.4	
k3 =	1.4	
θ =	0	
Kθ =	1	
ZIm =	719	
ZIs =	719	
ZII =	**331**	
ZIIIm =	414	
ZIIIs =	414	
ZIV =	475	

Several factors possibly influenced the change in yielding modes. First, the quality of the 4x6 material was very poor with the specific gravity results nearly half of those presented in NDS tables. Much of the wood material showed evidence of the pith and had few growth rings which resulted in the lower specific gravity and dowel embedment strength. Second the bolts used in this research were SAE J429 grade 2 which is the common bolt sold at hardware stores. The minimum yield strength of a SAE J429 grade 2 bolt is 57,000 psi which is significantly different than the value of 45,000 psi which is recommended by NDS.

Several alternative connection configurations were tested to see if Yield Mode III and IV could be obtained. Many variables exist which could be contributing to the wrong prediction of yield modes such as the number of bolts in the connection, the type of loading, the wood material, the bolt strength, and the bolt diameter. The alternate connection configurations were tested to determine whether which, if any, of these variables affected the yield mode predictions.

One test was performed using the 6D spacing for several configurations once it became apparent that the original connection configuration was not behaving according to the expected yield modes. In an attempt to attain Yield Mode III, the 0.25 in. plate was replaced with a 0.5 in. plate and fastened to a 4x6 piece of Mixed Southern Yellow Pine lumber with five 3/8 in. bolts and subjected to reverse cyclic loading. Yielding behavior was still Yield Mode II. Next a 4x6 piece of Mixed Southern Yellow Pine lumber with an approximate specific gravity of 0.25 was connected to a 2x6 piece of Southern Yellow Pine lumber with five 1/2 in. bolts and subjected to reverse cyclic loading in an attempt to attain Yield Mode III. Some slight bolt bending was present in one bolt, but behavior was mostly in accordance with Yield Mode II.

The next configuration tested was a 4x6 piece of Mixed Southern Yellow Pine lumber with approximate specific gravity of 0.51 bolted to a 2x6 piece of Southern Yellow Pine lumber with five 3/8 in. bolts and subjected to reverse cyclic loading. Bolts showed slight signs of bending. Bolts for this test can be seen in Figure 4.32 on the far right. The same connection configuration was repeated, but instead subjected to monotonic loading. Bolts again showed slight signs of bending. Bolts can be seen in Figure 4.32 beside those tested under reverse cyclic loading.

The next variation tested was the number of bolts present in the connection. First a single 3/8 in. bolt was tested connecting a 4x6 piece of Mixed Southern Yellow Pine lumber and a 2x6 piece of Southern Yellow Pine lumber and subjected to monotonic loading. The bolt was located 7 in. from the end of the material and displaced one inch. Yield Mode III was obtained and the bolt can be seen on the far left in Figure 4.32. The configuration was tested again using three 3/8 in. bolts spaced at 6D and subjected to monotonic loading. Bolt bending occurred and the bolts can be seen beside the single bolt in Figure 4.32.

Figure 4.32: Bolts from Alternate Connection Configurations.

The next alternate test was performed to determine whether the low specific gravity for the 4x6 material affected results. Because no 4x6 material with higher specific gravities were available, a fabricated 4x6 was formed and used in a test with a 0.25 in. steel plate connected with five 1/2 in. diameter bolts in accordance with the original Yield Mode III design configuration. Spacing was 6D and loading was reverse cyclic. The 4x6 was fabricated by gluing three 2x6 pieces of Southern Yellow Pine lumber together and planing to actual 4x6 dimensions (3.5 in. x 5.5 in.). The Southern Yellow Pine had approximate specific gravities of 0.55. Slight bolt bending occurred; however, behavior was mostly in accordance with Yield Mode II. No separation along the glue line was apparent. Ultimate failure was splitting of the 4x6 material along the bolt line. It was, therefore, concluded that better 4x6 material may not produce the Yield Mode III as predicted, thus, testing continued using the available material which had low specific gravity.

Testing performed by Anderson (2002) also experienced wrong yield mode predictions. He was able to obtain Yield Mode II, but had difficulty obtaining consistent results for the connection configurations which were predicted to yield in Modes III and IV. Anderson kept the spacing between bolts the same at 4D, but tested multiple numbers of bolts in connections and multiple rows under both monotonic and reverse cyclic loading.

To obtain Yield Mode III, Anderson (2002) tested a connection configuration utilizing a 4x6 Southern Yellow Pine bolted to a 0.25 in. steel plate with 3/8 in. bolts. First he tested a single bolt under monotonic loading which exhibited some Mode IV yielding but not Mode III. Next he tested a single row of five bolts under monotonic loading which exhibited mixed yielding between Mode II and Mode IV. Then he tested two rows of five bolts under monotonic loading and multiple plastic hinges formed in some bolts while others remained straight which is a mixture of Mode II and Mode IV behavior. The same connection configurations were also tested under cyclic loading. The single bolt exhibited signs of Yield Mode IV. The five bolts in a single row and double row both exhibited yielding between Modes II and IV. Also tested were three bolts in a single row and three bolts in double rows under cyclic loading where the yield modes ranged between II and IV. Anderson (2002) suggests that the reason Yield Mode III was not obtained was due to bolt end fixity provided by the nut and washer which the Yield Limit Model does not consider.

To obtain Yield Mode IV, Anderson (2002) tested a connection configuration utilizing two 4x6 Southern Yellow Pine bolted together with 3/8 in. bolts. A single bolt subjected to monotonic loading, five bolts in a single row, and five bolts in double rows all exhibited Yield Mode IV behavior. A single bolt subjected to reverse cyclic loading also exhibited Yield Mode IV behavior. Three bolts and five bolts in a single row under reverse cyclic loading yielded between Modes III and IV. Three bolts and five bolts in double rows under reverse cyclic loading also yielded between Modes III and IV. Anderson (2002) suggests that the bolts migrate through the yielding behaviors from Mode II to IV and that failure occurred by splitting of the wood before all the bolts could complete their migration to Mode IV thus there was indication of mixed yielding modes at failure.

Testing performed by Jorissen (1998) provides additional information on yield mode predictions. He tested several connection configurations with a variety of number of bolts and spacing. All his tests utilized double shear (two side members were present) and were subjected to monotonic loading (either tension or compression). He reported the bending angles that were present in the bolts after testing. As the number of bolts present in the connection increased, the angle(s) in the bolts decreased. His connection layout utilized a main member of 48 mm (1.89 in.) thick lumber and two side members of 24 mm (0.945 in.) thick lumber with either 11.25 mm (0.443 in.) or 11.75 mm. (0.463 in.) diameter bolts. He tested connections with three, five, and nine bolts and obtained Yield Mode III. The mean angle of the bolts from horizontal for the connections with three bolts was approximately 14 degrees. The mean angle from horizontal for the connections with five bolts was 10 degrees while the mean angle from horizontal for the connections with nine bolts was approximately 5 degrees. The only connection layout he tested that obtained Yield Mode IV had one bolt present and the angle from horizontal was 10 degrees. The layout utilized a main member of 72 mm (2.83 in.) and two side members of 59 mm (2.32 in) with a 11.75 mm (0.463 in) diameter bolt.