Chapter 4 Results and Discussion

4.1 – General

This test program was comprised of one hundred and eighty single-shear bolted timber connections loaded in a cyclic manner, parallel to grain. Connection variables included number of bolts, and number of rows of bolts with the intent of determining the significance of the group action factor at capacity across a wide range of connection geometries and expected yield modes. Cyclic displacement protocols were based on the results of an additional eleven sets of three monotonic connection tests for each of the three and five-bolt, single-row and five-bolt, two-row configurations.

This chapter provides the results of monotonic and cyclic tests in the form of load-displacement curves, and lists performance indicators such as capacity, 5% offset yield, equivalent energy elastic-plastic yield strength, equivalent elastic-plastic energy, elastic stiffness, and ductility. All monotonic test configurations had three replications and all cyclic test configurations had ten replications, unless otherwise noted.

Data analysis provided strength parameters and energy dissipation characteristics for the connection configurations. The normalization of connection properties based on single-bolt connection performance provided insight into the effects of multiple-bolt and multiple-row configurations on joint performance. The group action factor associated with strength properties of multiple-bolt connections, was analyzed at connection capacity and 5% offset yield strength based on the performance of single-bolt connections.

The Yield Limit Model (YLM) is used to predict the single-bolt design strength for a given connection geometry and material. Since multiple-bolt design is based on the YLM as well as the group action factor, interest is placed on the ability of the model to predict strength values of cyclically loaded, single-bolt joints. Dowel embedment and bolt bending stress data at capacity and 5% offset yield strength, was obtained for each member and bolt size to be used in the YLM model to predict a yield mode, 5% offset yield strength, and capacity. Model values were then compared to test values.

Future discussion of connection yield modes according to the YLM, requires a definition for mixed mode yield. Mixed mode yield refers to the yielding mechanism observed in multiple-bolt connections when not all bolts achieved the same yield mode. Observation of this behavior was typical in multiple-bolt connections when the expected yield mode involved plastic hinge formation within the bolts. On a bolt-by-bolt basis the observed yield mode can be different so that the overall yielding mechanism can be stated as a range of yield modes or simply mixed mode yield. This phenomenon is due to 1) misalignment of bolt holes (construction tolerances), 2) local variation in bearing strength of the wood, and 3) variation in the bending strength of the bolts.

For further discussion of failure modes, it is necessary to provide some insight into the assumptions made during the analysis of connection tests. For this study there were two classifications of failure mechanism: ductile and brittle. These classifications were subjective in nature, based on test observation and individual load-deflection plots. A ductile failure mechanism indicates that loss of strength after maximum load, occurred gradually as deformation continued at least until strength loss dropped below 80% of the maximum load. A brittle failure mechanism indicates that the loss of strength after maximum load occurred in an instantaneous manner so that over a small increment of additional deformation, the load decreased from the maximum load to well below the defined failure load of 80% maximum load. In addition a designated brittle failure is typically accompanied by a mode of failure such as splitting, tension rupture, plug shear, or block shear.

4.2 – Mode II Yield

Tested connections corresponding to yield mode II were constructed with 2 in. x 6 in. Southern Yellow Pine and 1/2 in. diameter bolts. Further information concerning geometry and test replication can be found in Tables 3.1 and 3.2.

4.2.1 –Monotonic Test Results

Single-bolt connections were tested in tension until failure. The three specimens tested were observed to have significant bolt rotation about the shear plane, but no indication of plastic hinge formation within the bolt, corresponding to yield mode II.

Failure was induced by splitting of timber material from the bolt-hole through the end distance of 7D.

Five-bolt, one-row connections were tested in compression until failure. The three specimens were observed to have higher than expected load carrying capacity beyond maximum load, due to confinement of split propagation by the fixture securing plate and lag screws. Bolts rotated about the shear plane and remained straight indicating mode II yield. Splitting of the timber member through the bolt row centerline accompanied failure.

Five-bolt, two-row connections were tested in tension until failure. The three specimens tested were observed to have rigid bolt rotation about the shear plane corresponding to yield mode II. In one specimen, failure was observed to occur due to a block shear between one bolt row and the edge of the timber member. In this case the immediate redistribution of load caused splitting through the centerline of the other row. In other specimens splitting occurred through one row on a member followed by splitting of the opposite row on the other member.

Connection and member properties are shown in Tables 4.1 and 4.2.

Table 4.1: 2X Series monotonic connection properties. Three replications per series unless otherwise noted.

	2X1R1M Series		2X1R5M Series		2X2R5M Series	
	Mean	**COV (%)**	**Mean**	**COV (%)**	**Mean**	**COV (%)**
Max Load (lbs)	3196.64	15.36	10062.46	11.99	16936.01	15.09
@ Displacement (in)	0.92	15.75	0.40	12.64	0.28	19.02
Load/Bolt (lbs)	3196.64		2012.49		1693.60	
Failure Load (lbs)	2412.95	16.55	8181.46	8.23	9706.04	64.68
@ Displacement (in)	0.99	14.37	0.56	35.64	0.31	21.22
Load/Bolt (lbs)	2412.95		1636.29		970.60	
40% Max (lbs)	1271.41	15.32	3978.73	11.18	6667.10	15.63
@ Displacement (in)	0.20	11.21	0.16	20.82	0.16	14.43
E.E.P. Yield (lbs)	2557.31	15.36	9427.39	11.80	15312.24	21.57
@ Displacement (in)	0.31	14.83	0.27	20.98	0.24	12.59
Load/Bolt (lbs)	2557.31		1885.48		1531.22	
5% Offset (lbs)	1512.69	14.88	8709.09	13.26	16488.35	11.41
@ Displacement (in)	0.24	7.54	0.28	18.07	0.27	15.14
Load/Bolt (lbs)	1512.69		1741.82		1648.83	
Elastic Stiff. (lb/in)	12230.46	28.68	50031.81	31.14	103839.12	19.03
E.E.P. Energy (lb*in)	2015.52	24.34	3553.53	32.41	2123.78	34.41
Ductility Ratio	3.24	7.13	2.05	19.13	1.28	14.33

E.E.P. Yield: Equivalent Energy Elastic-Plastic Yield
E.E.P. Energy: Equivalent Elastic-Plastic Energy

Table 4.2: 2X Series monotonic member properties. Three replications per series unless otherwise noted.

	2X1R1M Series		2X1R5M Series		2X2R5M Series	
Member A	**Mean**	**COV (%)**	**Mean**	**COV (%)**	**Mean**	**COV (%)**
M.C. (%)	11.36	3.99	11.57	5.41	12.63	15.47
Specific Gravity	0.56	13.00	0.62	16.32	0.60	7.26
D.E. 5% Yield (psi)	6423.04	17.86	7016.50	16.78	6656.78	6.44
D.E. Capacity (psi)	6460.43	17.11	7112.41	17.01	6687.58	5.78
Member B						
M.C. (%)	11.55	11.54	13.00	9.71	12.20	10.36
Specific Gravity	0.58	1.98	0.63	12.90	0.54	10.14
D.E. 5% Yield (psi)	6239.60	2.48	5919.08	26.88	5278.74*	25.02
D.E. Capacity (psi)	6310.74	4.28	5998.62	25.25	5394.46*	27.21

* Two replications
D.E.: Dowel Embeddment Test Data

4.2.2 – Cyclic Test Results

Single-bolt connections were exposed to a displacement controlled cyclic protocol as described in Section 3.5.1, where $\Delta = 0.6$ in. In all tests, bolts remained straight and pivoted about the shear plane, typical of mode II yield. The two failure modes noted throughout the testing were splitting, or tear-out through the end of a member (Figure 4.1). A typical load-deflection plot with indication of brittle failure is shown in Figure 4.2.

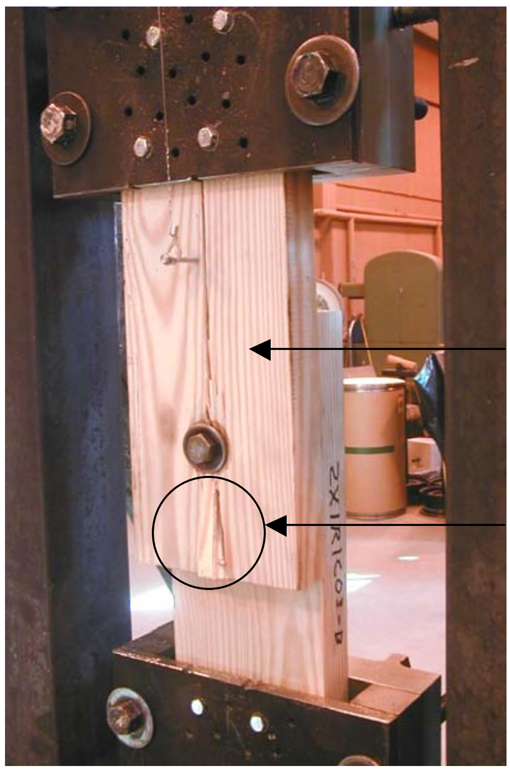

Figure 4.1: Photograph of typical 2X1R1C Series failure.

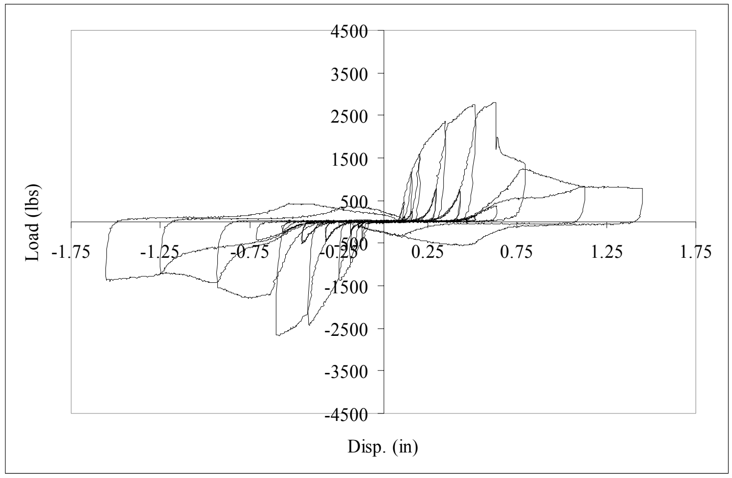

Figure 4.2: Typical load-deflection plot. 2X1R1C Series.

Three-bolt, one-row connections were exposed to a displacement controlled cyclic protocol as described in Section 3.5.1, where $\Delta = 0.44$ in. In all tests the bolts remained straight and pivoted about the shear plane, typical of mode II yield. Two failure modes noted were splitting or tear-out through the centerline of the bolt row (Figure 4.3). Typically, tear-out occurred between bolts in a row, while splitting propagated away from the connection at the outer most bolts. A typical load-deflection plot with indication of a brittle failure is shown in Figure 4.4.

Figure 4.3: Photograph of typical 2X1R3C Series failure.

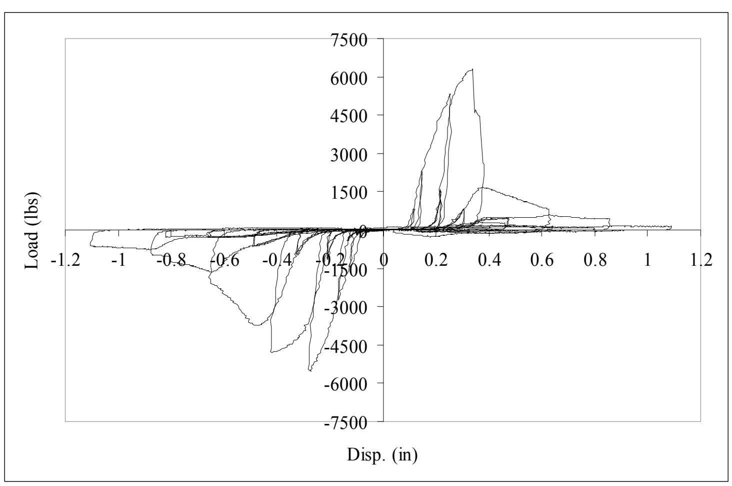

Figure 4.4: Typical load-deflection plot. 2X1R3C Series.

Five-bolt, one-row connections were exposed to a displacement controlled cyclic protocol as described in Section 3.5.1, where $\Delta = 0.27$ in. In all tests, bolts remained straight and pivoted about the shear plane, typical of mode II yield. The dominant mode of failure was splitting through the centerline of the bolt row (Figure 4.5). A typical load-deflection plot with indication of brittle failure is shown in Figure 4.6.

Figure 4.5: Photograph of typical 2X1R5C Series failure.

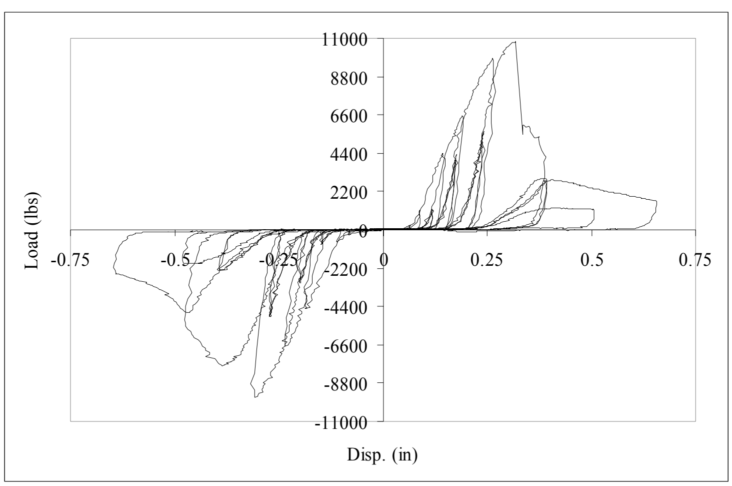

Figure 4.6: Typical load-deflection plot. 2X1R5C Series.

Three-bolt, two-row connections were exposed to a displacement controlled cyclic protocol as described in Section 3.5.1, where $\Delta = 0.35$ in. In all tests, bolts remained straight and pivoted about the shear plane, typical of mode II yield. The two failure modes noted throughout the testing were splitting through the centerline of one row of bolts on each member or through both rows on one member, or block shear of the material between the rows (Figure 4.7). A typical load-deflection plot with indication of brittle failure is shown in Figure 4.8.

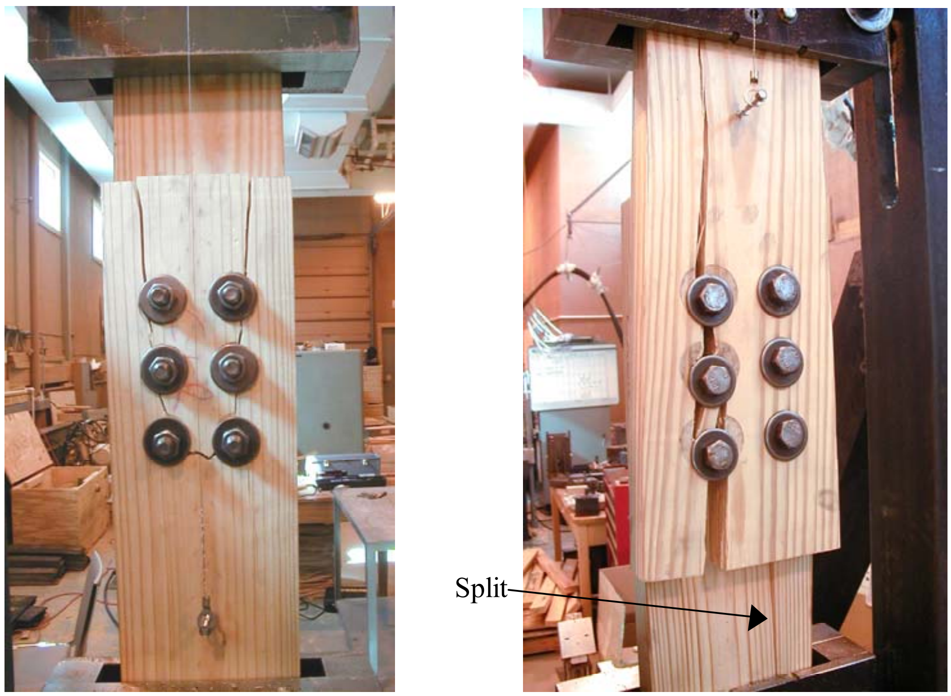

Figure 4.7: Photograph of typical 2X2R3C Series failure.

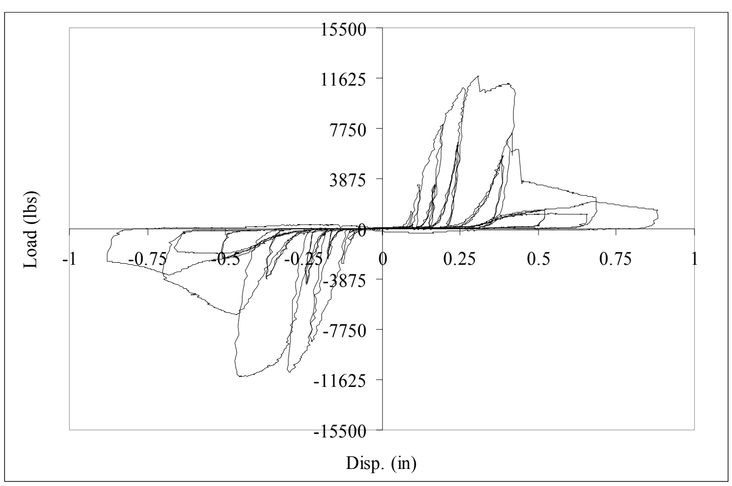

Figure 4.8: Typical load-deflection plot. 2X2R3C Series.

Five-bolt, two-row connections were exposed to a displacement controlled cyclic protocol as described in Section 3.5.1, where $\Delta = 0.27$ in. In all tests, bolts remained straight and pivoted about the shear plane, typical of mode II yield. Failure modes were noted as splitting, block shear, and tension rupture (Figure 4.9). Specimens that had splitting as the primary mode of failure typically split through the centerline of one row of bolts on both members or both rows of bolts on one member. Tension rupture failures typically occurred through the first row of bolts in the direction of loading, and involved the rupture of the entire cross-section. Block shear failures involved either the wood between bolt rows or the wood along the outside edge of a bolt row. A typical load-deflection plot with indication of a brittle failure is shown in Figure 4.10.

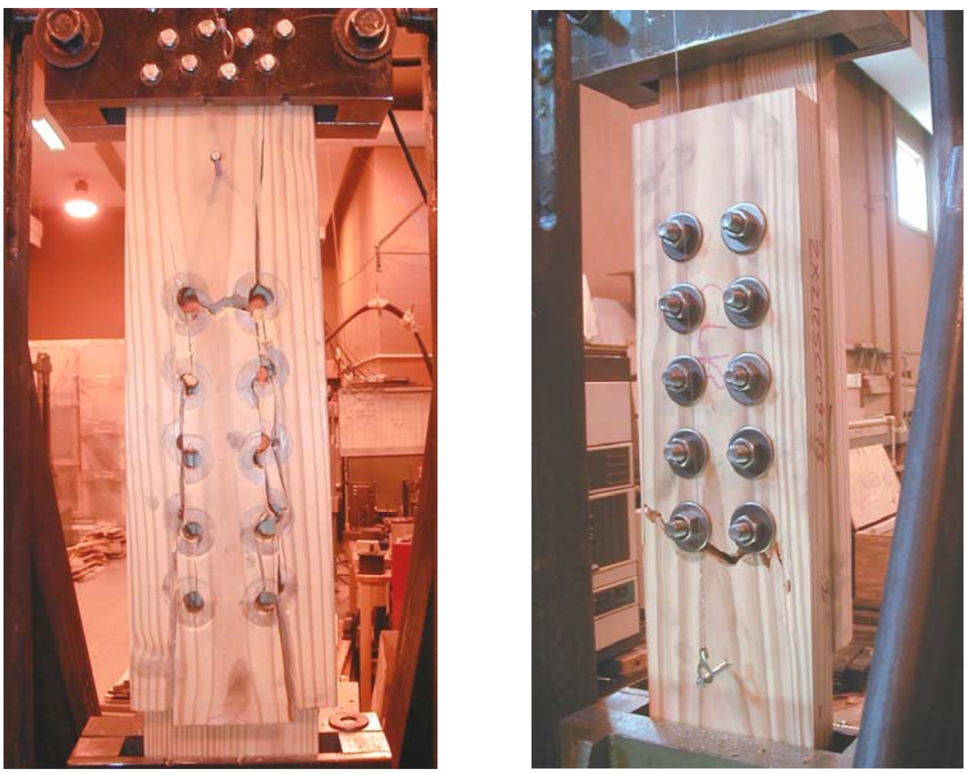

Figure 4.9: Photograph of typical 2X2R5C Series failure.

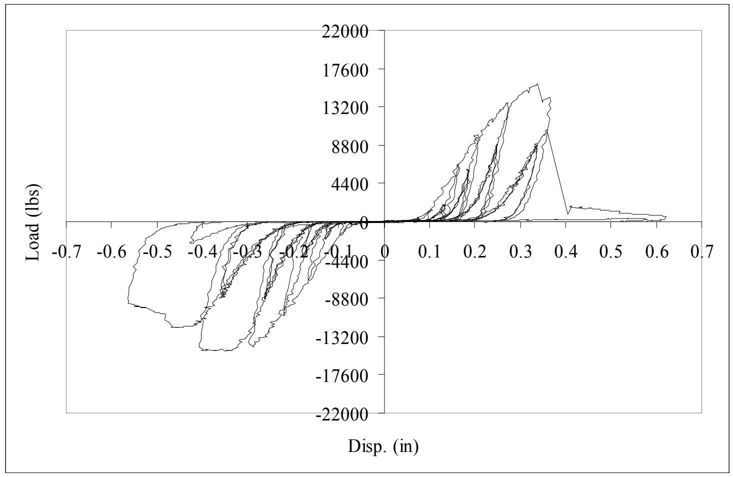

Figure 4.10: Typical load-deflection plot. 2X2R5C Series.

Connection and member properties for the 2X Series, constructed of 2 in. x 6 in. Southern Yellow Pine and 1/2 in. diameter bolts can be found in Table 4.3 and Table 4.4. Results indicate that prediction of mode II yield was accurate since the primary yielding mechanism was crushing of wood under a bolt that remained straight and rotated about the shear plane.

Connections within this series generally failed in a brittle manner at or just beyond the displacement at capacity. Load-deflection plots of single-bolt connections showed typical inelastic behavior after yielding. Multiple-bolt connections generally had very small inelastic regions, most likely due to the uneven load distribution among bolts in a row causing high, localized stresses around one or more bolt-holes, or as a result of the localized failures due to over-stress of the wood material between bolts. The latter cause could possibly be corrected by increasing the bolt spacing.

Table 4.3: 2X Series cyclic connection properties. Ten replications per series unless otherwise noted.

	2X1R1C Series		2X1R3C Series		2X1R5C Series	
	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)
Max Load (lbs)	2769.63	20.86	5985.78	9.87	8677.16	10.16
@ Displacement (in)	0.72	33.28	0.30	13.70	0.30	6.15
Load/Bolt (lbs)	2769.63		1995.26		1735.43	
Failure Load (lbs)	2215.70	20.86	4788.62	9.87	6941.73	10.16
@ Displacement (in)	0.72	33.28	0.30	13.70	0.30	6.41
Load/Bolt (lbs)	2215.70		1596.21		1388.35	
40% Max (lbs)	1107.85	20.86	2394.31	9.87	3470.86	10.16
@ Displacement (in)	0.19	18.37	0.15	6.07	0.16	5.72
E.E.P. Yield (lbs)	2315.05	18.67	5226.16	11.70	7793.15	13.93
@ Displacement (in)	0.32	20.51	0.23	9.56	0.24	7.58
Load/Bolt (lbs)	2315.05		1742.05		1558.63	
5% Offset (lbs)	1603.90	15.00	5253.00	9.62	8178.00	13.43
@ Displacement (in)	0.27	12.70	0.25	6.47	0.28	5.96
Load/Bolt (lbs)	1603.90		1751.00		1635.60	
Elastic Stiff. (lb/in)	10001.72	23.11	36578.69	13.33	48672.62	11.28
E.E.P. Energy (lb*in)	1281.53	57.75	767.79	32.90	1059.38	17.75
Ductility Ratio	2.25	20.51	1.33	8.36	1.25	4.78

	2X2R3C Series		2X2R5C Series	
	Mean	COV (%)	Mean	COV (%)
Max Load (lbs)	11892.30	11.88	16601.90	13.88
@ Displacement (in)	0.39	25.76	0.32	11.03
Load/Bolt (lbs)	1982.05		1660.19	
Failure Load (lbs)	9513.84	11.88	13281.52	13.88
@ Displacement (in)	0.40	23.35	0.33	10.73
Load/Bolt (lbs)	1585.64		1328.15	
40% Max (lbs)	4756.92	11.88	6640.76	13.88
@ Displacement (in)	0.17	9.30	0.16	6.64
E.E.P. Yield (lbs)	10747.95	10.63	15652.23	14.15
@ Displacement (in)	0.27	12.97	0.27	9.68
Load/Bolt (lbs)	1791.32		1565.22	
5% Offset (lbs)	10873.68	13.47	16149.40	15.50
@ Displacement (in)	0.32	14.43	0.31	9.80
Load/Bolt (lbs)	1812.28		1614.94	
Elastic Stiff. (lb/in)	56223.88	22.55	83111.81	15.55
E.E.P. Energy (lb*in)	2400.84	43.53	2596.70	25.29
Ductility Ratio	1.44	13.86	1.27	9.39

E.E.P. Yield: Equivalent Elastic-Plastic Yield
E.E.P. Energy: Equivalent Elastic-Plastic Energy

Table 4.4: 2X Series cyclic member properties. Ten replications per series unless otherwise noted.

	2X1R1C Series		2X1R3C Series		2X1R5C Series	
Member A	**Mean**	**COV (%)**	**Mean**	**COV (%)**	**Mean**	**COV (%)**
M.C. (%)	12.86	15.66	11.77	6.67	12.68	11.71
Specific Gravity	0.55	10.17	0.59	13.44	0.57	11.03
D.E. 5% Yield (psi)	5363.34	16.60	6483.53	20.57	5984.21	16.53
D.E. Capacity (psi)	5500.43	17.10	6587.38	20.17	6080.91	16.15
Member B						
M.C. (%)	13.24	8.30	12.51	8.26	12.65	12.30
Specific Gravity	0.56	12.37	0.62	18.69	0.55	9.07
D.E. 5% Yield (psi)	5669.02	23.55	6074.28	12.93	5598.94	18.10
D.E. Capacity (psi)	5734.32	22.88	6206.21	12.60	5703.07	17.88

	2X2R3C Series		2X2R5C Series	
Member A	**Mean**	**COV (%)**	**Mean**	**COV (%)**
M.C. (%)	13.06	10.15	12.46	10.90
Specific Gravity	0.57	10.25	0.53	14.67
D.E. 5% Yield (psi)	5811.25	22.72	5113.82	22.40
D.E. Capacity (psi)	5971.10	23.18	5221.24	23.16
Member B				
M.C. (%)	13.12	5.70	12.69	9.77
Specific Gravity	0.56	14.96	0.55	9.10
D.E. 5% Yield (psi)	5163.21	22.63	5074.33	13.82
D.E. Capacity (psi)	5307.03	22.65	5181.19	13.95

D.E.: Dowel Embedment Test Data

4.3 – Mode III Yield

Tested connections corresponding to yield mode III were constructed with a 4 in. x 6 in. Southern Yellow Pine main member, a 1/4 in. steel side plate, and 3/8 in. diameter bolts. Further information concerning geometry and test replication can be found in Tables 3.1 and 3.2.

4.3.1 – Monotonic Test Results

Single-bolt connections were tested in tension until failure. The three specimens tested were observed to have significant wood crushing and bolt bending as the yielding mechanism. Bolt bending occurred at the shear plane and in a gradual arc through the thickness of the wood member, not exactly corresponding to yield mode IV and definitely not a mode III yield. Failure was caused by a sudden split in the wood material near the bolt-hole, possibly caused by tension perpendicular to grain due to bolt tensioning at large deformations and the corresponding compression on the wood member under the washers. It should also be noted that shear yielding of the bolt occurred at the shear plane causing a visible notch at the hinge location.

Five-bolt, one-row connections were tested in tension until failure. Permanent bolt deformation was visually non-existent in many cases, and so the connections were defined as undergoing mixed mode yielding. For these tests yielding was observed to range between mode II and mode IV. Splitting of the timber member through the bolt row centerline caused failure.

Five-bolt, two-row connections were tested in tension until failure. The three specimens tested were observed to have multiple plastic hinge formation in some bolts, one at the shear plane and one within the wood member, while other bolts appeared to remain straight. For these tests yielding was observed to vary between mode II and mode IV. In two specimens, failure was caused by splitting through the centerline of one of the rows followed by a rupture through the rest of the cross section corresponding to a block shear failure.

Connection and member properties are shown in Tables 4.5 and 4.6.

Table 4.5: ST Series monotonic connection properties. Three replications per series unless otherwise noted.

	ST1R1M Series		**ST1R5M Series**		**ST2R5M Series**	
	Mean	**COV (%)**	**Mean**	**COV (%)**	**Mean**	**COV (%)**
Max Load (lbs)	3606.43	12.72	9142.01	18.99	21208.89	17.25
@ Displacement (in)	1.36	7.79	0.23	27.57	0.34	10.20
Load/Bolt (lbs)	3606.43		1828.40		2120.89	
Failure Load (lbs)	3386.13	7.68	6568.62	6.29	14923.47	52.75
@ Displacement (in)	1.41	10.72	0.32	10.17	0.47	23.29
Load/Bolt (lbs)	3386.13		1313.72		1492.35	
40% Max (lbs)	1396.88	13.55	3568.90	20.19	8369.71	17.61
@ Displacement (in)	0.14	28.14	0.06	25.69	0.12	10.62
E.E.P. Yield (lbs)	2920.46	11.47	8217.26	14.70	19685.66	18.27
@ Displacement (in)	0.25	12.13	0.14	21.18	0.26	3.88
Load/Bolt (lbs)	2920.46		1643.45		1968.57	
5% Offset (lbs)	1755.16	10.41	7147.70	13.81	18911.57	24.96
@ Displacement (in)	0.19	17.42	0.14	14.65	0.27	5.09
Load/Bolt (lbs)	1755.16		1429.54		1891.16	
Elastic Stiff. (lb/in)	13820.08	17.56	56827.17	8.19	80806.23	16.39
E.E.P. Energy (lb*in)	3701.48	23.78	2069.27	19.37	6535.40	36.24
Ductility Ratio	5.68	20.01	2.25	25.36	1.80	20.41

E.E.P. Yield: Equivalent Energy Elastic-Plastic Yield
E.E.P. Energy: Equivalent Elastic-Plastic Energy

Table 4.6: ST Series monotonic member properties. Three replications per series unless otherwise noted.

	ST1R1M Series		**ST1R5M Series**		**ST2R5M Series**	
	Mean	**COV (%)**	**Mean**	**COV (%)**	**Mean**	**COV (%)**
M.C. (%)	14.87	5.52	16.26	9.64	14.22	11.17
Specific Gravity	0.46	20.74	0.56	13.48	0.48	19.04
D.E. 5% Yield (psi)	4284.23	11.20	4715.43	13.16	4484.84	36.16
D.E. Capacity (psi)	4496.74	12.51	5064.59	14.99	4824.14	40.89

D.E.: Dowel Embeddment Test Data

4.3.2 – Cyclic Test Results

Single-bolt connections were exposed to a displacement controlled cyclic protocol as described in Section 3.5.1, where $\Delta = 0.69$ in. In all tests there were two hinge formations within the bolt, typical of mode IV yield. Connection failure was caused by the fatigue of the bolt at the shear plane as a result of repetitive bending (Figure 4.11). A typical load-deflection plot showing brittle failure is shown in Figure 4.12. It should be noted that this kind of fatigue was only recognized in single-bolt connections at high levels of displacement (> 1 inch).

Figure 4.11: Photograph of typical ST1R1C Series failure.

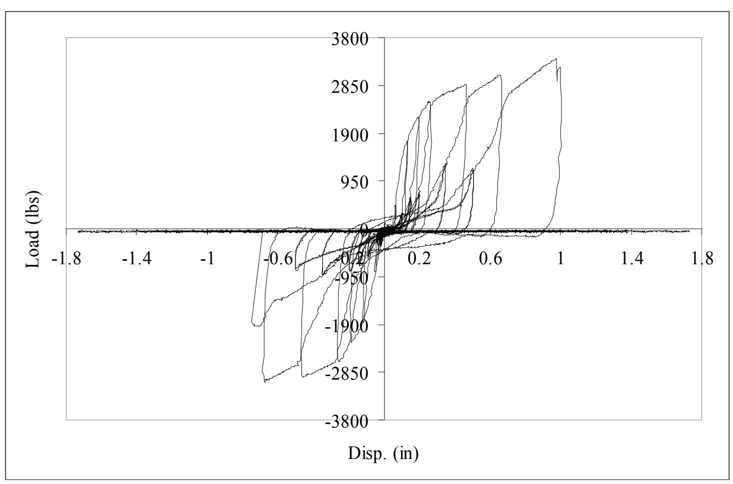

Figure 4.12: Typical load-deflection plot. ST1R1C Series.

Three-bolt, one-row connections were exposed to a displacement controlled cyclic protocol as described in Section 3.5.1, where $\Delta = 0.27$ in. Generally, the observed yielding mechanism was hard to characterize as a result of the difference between slight hinge formation and no formation at all. The yield modes were noted as ranging between mode II and mode IV for each specimen. The dominant failure mode was splitting of the wood member through the centerline of the bolt row (Figure 4.13). A typical load-deflection plot with indication of brittle failure is shown in Figure 4.14.

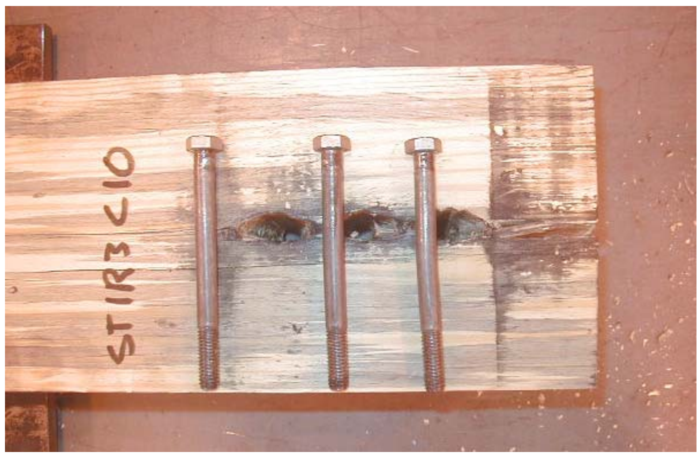

Figure 4.13: Photograph of typical ST1R3C Series failure.

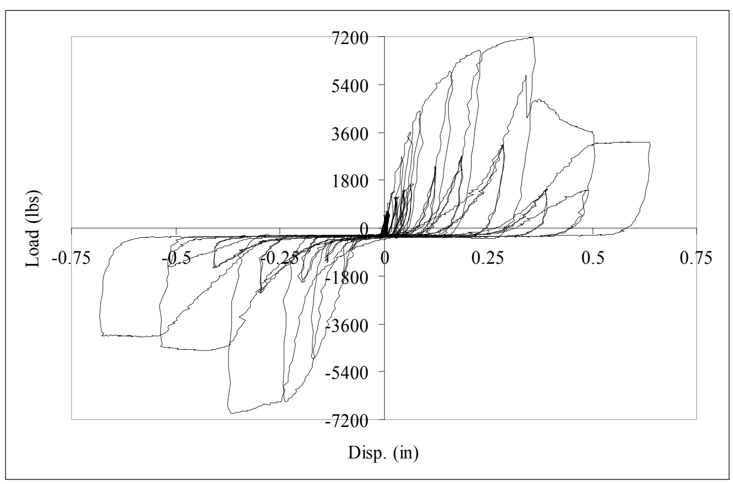

Figure 4.14: Typical load-deflection plot. ST1R3C Series.

Five-bolt, one-row connections were exposed to a displacement controlled cyclic protocol as described in Section 3.5.1, where $\Delta = 0.27$ in.. Due to the relatively small displacement at which failure occurred, it was hard to determine the exact yield mode for each bolt. For this group of tests the yield mode ranged from between mode II and mode IV for each specimen. Failure occurred by splitting through the centerline of the bolt row (Figure 4.15). A typical load-deflection plot with indication of brittle failure is shown in Figure 4.16.

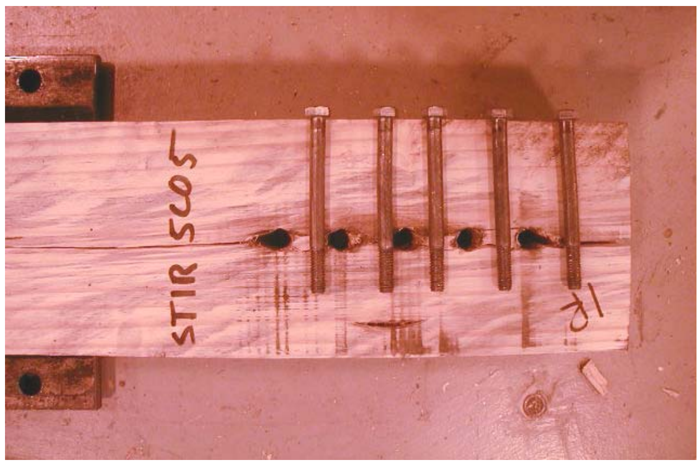

Figure 4.15: Photograph of typical ST1R5C Series failure.

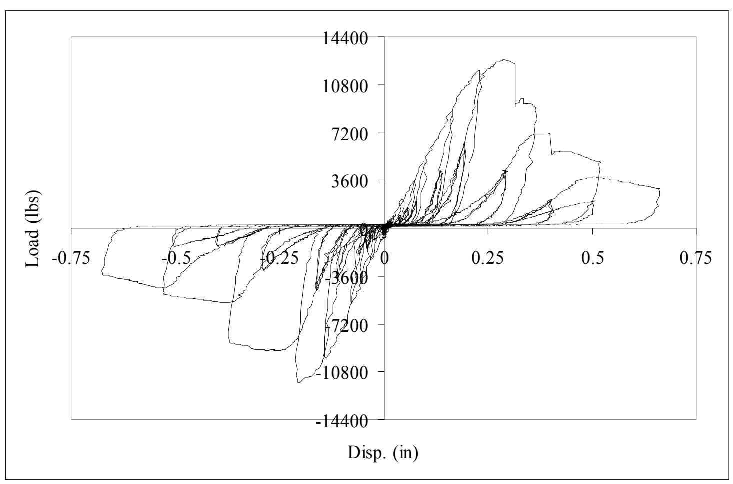

Figure 4.16: Typical load-deflection plot. ST1R5C Series.

Three-bolt, two-row connections were exposed to a displacement controlled cyclic protocol as described in Section 3.5.1, where $\Delta = 0.36$ in. In most of the connection specimens multiple hinges formed in the bolts, consistent with mode IV yield, yet it should be noted that several connections displayed a mixed mode yield of mode II and mode IV. The failure mode for all specimens was splitting through the centerline of the bolt rows (Figure 4.17). A typical load-deflection plot with indication of a ductile failure is shown in Figure 4.18.

Figure 4.17: Photograph of typical ST2R3C Series failure.

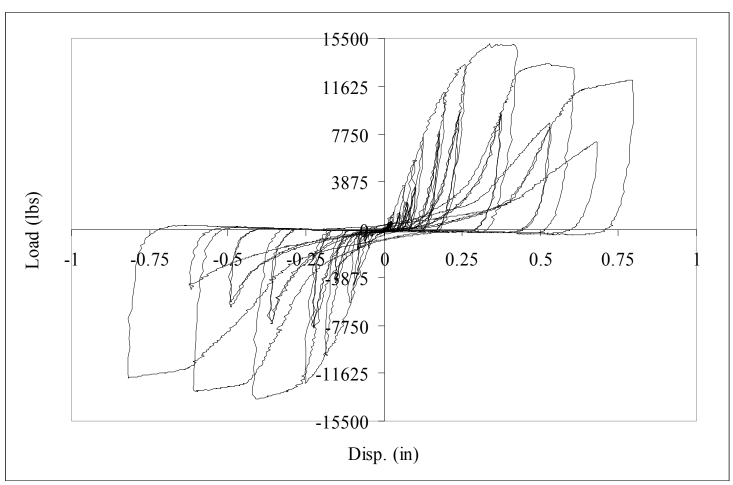

Figure 4.18: Typical load-deflection plot. ST2R3C Series.

Five-bolt, two-row connections were exposed to a displacement controlled cyclic protocol as described in Section 3.5.1, where $\Delta = 0.36$ in. Typically, a specimen within this series had a yield mode that ranged between mode II and mode IV. The most dominant mode of failure was splitting through the centerline of the bolt rows (Figure 4.19). Two of the specimens had a block shear failure in which a split in one row was immediately followed by a block shear failure through the other row involving the edge material. A typical load-deflection plot with indication of brittle failure is shown in Figure 4.20.

Figure 4.19: Photograph of typical ST2R5C Series failure.

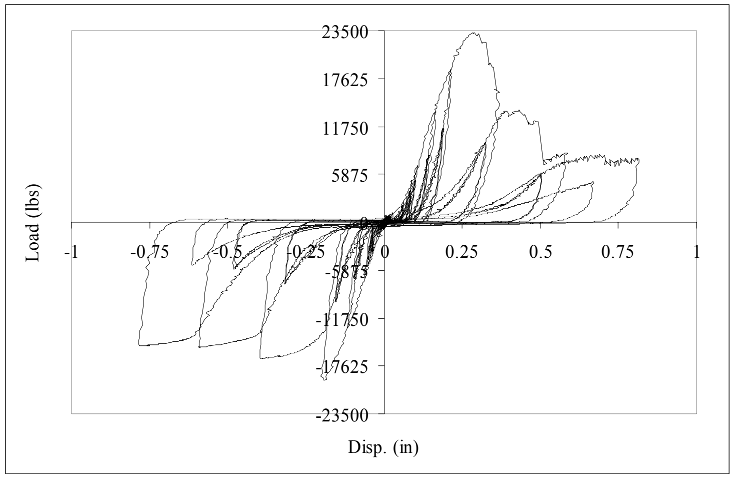

Figure 4.20: Typical load-deflection plot. ST2R5C Series.

Connection and member properties for the ST Series, constructed of 4 in. x 6 in. Southern Yellow Pine main members, 1/4 in. steel side plates, and 3/8 in. diameter bolts, can be found in Table 4.7 and Table 4.8. Results indicate that the prediction of a mode III yielding mechanism, using the Yield Limit Model, was not accurate and perhaps not possible due to the bolt end fixity provided by nut and washer. The Yield Limit Model does not account for end fixity.

Bolted connections within this series exhibited both ductile and brittle failure mechanisms. Load-deflection plots of single-bolt connections showed a significant non-linear region due to the plastic hinge formation within the bolt until the bolt failed due to fatigue and yielding at the sharp edge of the hole in the metal side plate. Three-bolt connections were typically mixed between ductile and brittle failure and analyzed accordingly. Five-bolt connections typically failed in a brittle manner and had indication of a range of yield modes.

Table 4.7: ST Series cyclic connection properties. Ten replications per series unless otherwise noted.

	ST1R1C Series		ST1R3C Series		ST1R5C Series	
	Mean	**COV (%)**	**Mean**	**COV (%)**	**Mean**	**COV (%)**
Max Load (lbs)	3031.76	7.26	6361.49	9.22	9949.80	15.72
@ Displacement (in)	0.80	15.89	0.27	25.01	0.19	18.84
Load/Bolt (lbs)	3031.76		2120.50		1989.96	
Failure Load (lbs)	2425.41	7.26	5089.20	9.22	7959.84	15.72
@ Displacement (in)	0.84	9.88	0.38	45.68	0.20	18.91
Load/Bolt (lbs)	2425.41		1696.40		1591.97	
40% Max (lbs)	1212.70	7.26	2544.60	9.22	3979.92	15.72
@ Displacement (in)	0.09	11.47	0.08	11.42	0.07	17.12
E.E.P. Yield (lbs)	2701.45	7.09	5614.76	9.69	9152.96	22.01
@ Displacement (in)	0.17	13.84	0.15	18.20	0.15	20.90
Load/Bolt (lbs)	2701.45		1871.59		1830.59	
5% Offset (lbs)	1978.25	12.42	5128.89	14.88	9604.41	18.66
@ Displacement (in)	0.21	72.16	0.17	21.55	0.18	23.69
Load/Bolt (lbs)	1978.25		1709.63		1920.88	
Elastic Stiff. (lb/in)	19770.49	19.18	50811.20	32.97	60155.31	21.08
E.E.P. Energy (lb*in)	2030.31	11.95	1713.93	57.63	1077.60	33.66
Ductility Ratio	5.18	12.33	2.76	39.94	1.36	11.00

	ST2R3C Series		ST2R5C Series	
	Mean	**COV (%)**	**Mean**	**COV (%)**
Max Load (lbs)	13037.50	9.99	19560.05	7.76
@ Displacement (in)	0.40	37.83	0.28	22.80
Load/Bolt (lbs)	2172.92		1956.01	
Failure Load (lbs)	10430.00	9.99	15648.04	7.76
@ Displacement (in)	0.65	22.27	0.31	39.06
Load/Bolt (lbs)	1738.33		1564.80	
40% Max (lbs)	5215.00	9.99	7824.02	7.76
@ Displacement (in)	0.10	12.03	0.10	15.22
E.E.P. Yield (lbs)	12019.49	10.99	17972.12	9.99
@ Displacement (in)	0.20	12.59	0.20	17.50
Load/Bolt (lbs)	2003.25		1797.21	
5% Offset (lbs)	11786.92	12.62	18711.82	9.49
@ Displacement (in)	0.29	28.58	0.25	17.08
Load/Bolt (lbs)	1964.49		1871.18	
Elastic Stiff. (lb/in)	68506.89	17.27	100872.97	18.70
E.E.P. Energy (lb*in)	6533.52	32.72	3660.30	53.29
Ductility Ratio	3.36	28.12	1.63	40.41

E.E.P. Yield: Equivalent Elastic-Plastic Yield
E.E.P. Energy: Equivalent Elastic-Plastic Energy

Table 4.8: ST Series cyclic member properties. Ten replications per series unless otherwise noted.

	ST1R1C Series		ST1R3C Series		ST1R5C Series	
	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)
M.C. (%)	14.80	7.28	15.58	8.05	13.51	16.20
Specific Gravity	0.49	12.54	0.49	10.12	0.55	16.03
D.E. 5% Yield (psi)	4614.75	12.75	3865.00**	10.80	5084.86	17.60
D.E. Capacity (psi)	5071.05	12.75	4199.62**	10.80	5493.93	17.60

	ST2R3C Series		ST2R5C Series	
	Mean	COV (%)	Mean	COV (%)
M.C. (%)	14.94*	9.43	14.47	8.72
Specific Gravity	0.51	18.58	0.54	14.72
D.E. 5% Yield (psi)	4646.08	23.37	4349.28	15.19
D.E. Capacity (psi)	5043.66	21.82	4649.73	13.04

* Nine Replications
** Seven Replications
D.E.: Dowel Embedment Test Data

4.4 – Mode IV Yield (3/8” Bolts)

Tested connections corresponding to yield mode IV were constructed with 4 in. x 6 in. Southern Yellow Pine and 3/8 in. diameter bolts. Further information concerning geometry and test replication can be found in Tables 3.1 and 3.2.

4.4.1 – Monotonic Test Results

Single-bolt connections were tested in tension and displaced to the limits of the testing machine and fixture. The three specimens tested were observed to have two hinge formations in the bolt, corresponding to yield mode IV. Failure could not be attained due to the displacement limitations of the equipment.

Five-bolt, one-row connections were tested in tension until failure. The three specimens tested were observed to have two hinge formations in all bolts, corresponding to yield mode IV. Splitting of the timber member through the bolt row centerline corresponded to failure although it should be noted, strength loss was not catastrophic in nature.

Five-bolt, two-row connections were tested in tension until failure. The three specimens tested were observed to have two hinge formations in all bolts, corresponding to yield mode IV. In two specimens failure was observed to occur due to splitting through the centerline of one row of bolts on both members. One of the specimens failed in block shear pattern corresponding to a split through one row of bolts and a tension rupture through the rest of the cross section.

Connection and member properties are shown in Tables 4.9 and 4.10.

Table 4.9: 46 Series monotonic connection properties. Three replications per series unless otherwise noted.

	461R1M Series		**461R5M Series**		**462R5M Series**	
	Mean	**COV (%)**	**Mean**	**COV (%)**	**Mean**	**COV (%)**
Max Load (lbs)	2366.48	5.79	7245.13	11.68	14248.57	6.40
@ Displacement (in)	1.54	1.59	0.48	9.85	0.47	21.02
Load/Bolt (lbs)	2366.48		1449.03		1424.86	
Failure Load (lbs)	2366.48	5.79	5504.09	12.65	10055.16	25.49
@ Displacement (in)	1.54	1.59	0.68	18.20	0.61	32.27
Load/Bolt (lbs)	2366.48		1100.82		1005.52	
40% Max (lbs)	926.37	8.26	2838.38	9.86	5592.99	5.81
@ Displacement (in)	0.19	20.22	0.11	5.37	0.16	28.44
E.E.P. Yield (lbs)	1893.19	5.79	6810.60	13.20	13729.52	3.50
@ Displacement (in)	0.32	17.02	0.24	4.15	0.33	26.60
Load/Bolt (lbs)	1893.19		1362.12		1372.95	
5% Offset (lbs)	1143.55	8.68	5916.37	13.06	12015.03	5.40
@ Displacement (in)	0.24	17.33	0.23	6.76	0.32	24.33
Load/Bolt (lbs)	1143.55		1183.27		1201.50	
Elastic Stiff. (lb/in)	7992.21	9.69	29936.58	14.69	50317.54	26.76
E.E.P. Energy (lb*in)	2509.59	1.57	3760.91	24.73	5729.48	47.50
Ductility Ratio	5.01	20.42	2.84	14.32	1.88	33.69

E.E.P. Yield: Equivalent Energy Elastic-Plastic Yield
E.E.P. Energy: Equivalent Elastic-Plastic Energy

Table 4.10: 46 Series monotonic member properties. Three replications per series unless otherwise noted.

	461R1M Series		**461R5M Series**		**462R5M Series**	
Member A	**Mean**	**COV (%)**	**Mean**	**COV (%)**	**Mean**	**COV (%)**
M.C. (%)	16.60	3.53	16.39	9.98	15.82	1.63
Specific Gravity	0.49	12.39	0.45	13.33	0.47	27.49
D.E. 5% Yield (psi)	4289.91	1.35	4278.41	15.19	4537.75	18.19
D.E. Capacity (psi)	4712.98	3.90	4712.41	14.69	4932.10	17.93
Member B						
M.C. (%)	16.27	5.15	16.91	28.25	14.38	4.21
Specific Gravity	0.48	8.61	0.51	15.62	0.59	21.34
D.E. 5% Yield (psi)	4716.86	18.83	4870.04	12.71	4558.11	13.03
D.E. Capacity (psi)	5192.98	14.12	5348.41	12.09	5100.44	8.78

D.E.: Dowel Embeddment Test Data

4.4.2 – Cyclic Test Results

Single-bolt connections were exposed to a displacement controlled cyclic protocol as described in Section 3.5.1, where $\Delta = 0.8$ in. In all tests there were two hinge formations within the bolt, typical of mode IV yield (Figure 4.21). Generally, the connection did not exhibit strength loss even after 2 in. of relative displacement. A typical load-deflection plot with undetermined failure mechanism is shown in Figure 4.22.

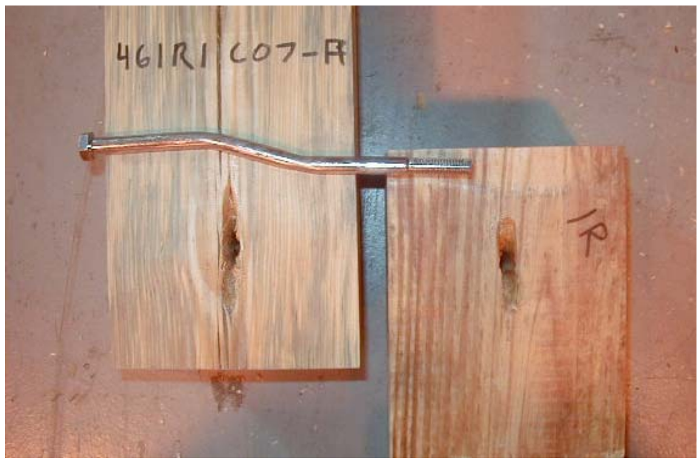

Figure 4.21: Photograph of typical 461R1C Series yield.

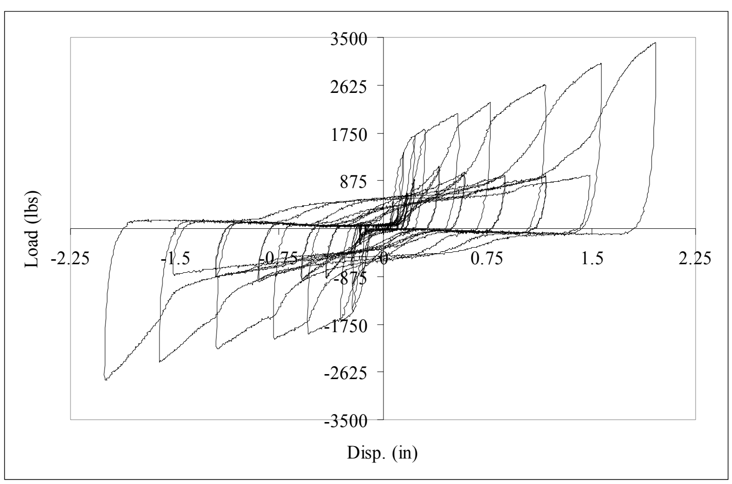

Figure 4.22: Typical load-deflection plot. 461R1C Series.

Three-bolt, one-row connections were exposed to a displacement controlled cyclic protocol as described in Section 3.5.1, where $\Delta = 0.51$ in. The typical yielding mechanism was noted as ranging between mode III and mode IV. The dominant failure mode was splitting of one member through the centerline of the bolt row (Figure 4.23). A typical load-deflection plot with indication of a ductile failure is shown in Figure 4.24.

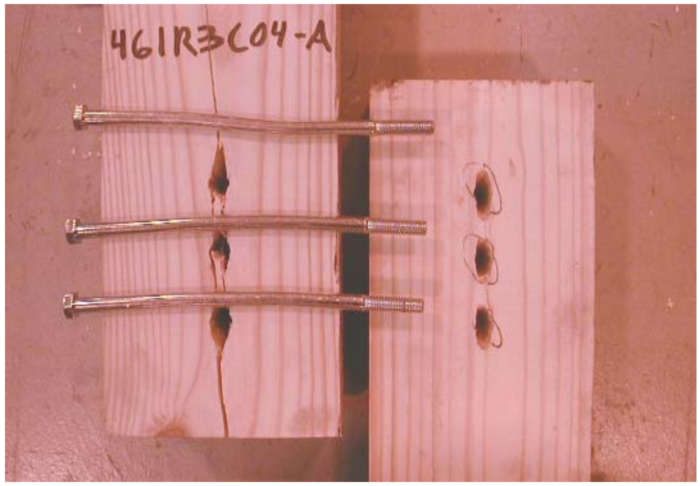

Figure 4.23: Photograph of typical 461R3C Series failure.

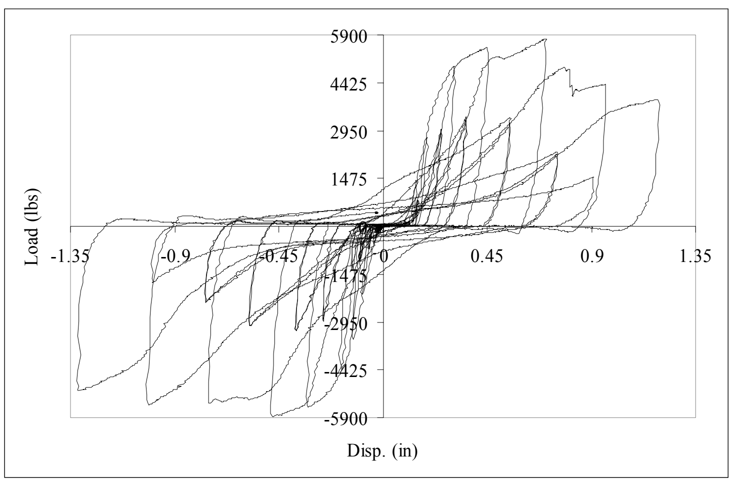

Figure 4.24: Typical load-deflection plot. 461R3C Series.

Five-bolt, one-row connections were exposed to a displacement controlled cyclic protocol as described in Section 3.5.1, where $\Delta = 0.46$ in.. All connection specimens in this series yielded in a mixed mode manner such that either mode III or mode IV was evident on a bolt-by-bolt basis. In general mode III yield was the more dominant yielding mechanism. Failure occurred by way of splitting through the centerline of the bolt row (Figure 4.25). A typical load-deflection plot with indication of brittle failure is shown in Figure 4.26.

Figure 4.25: Photograph of typical 461R5C Series failure.

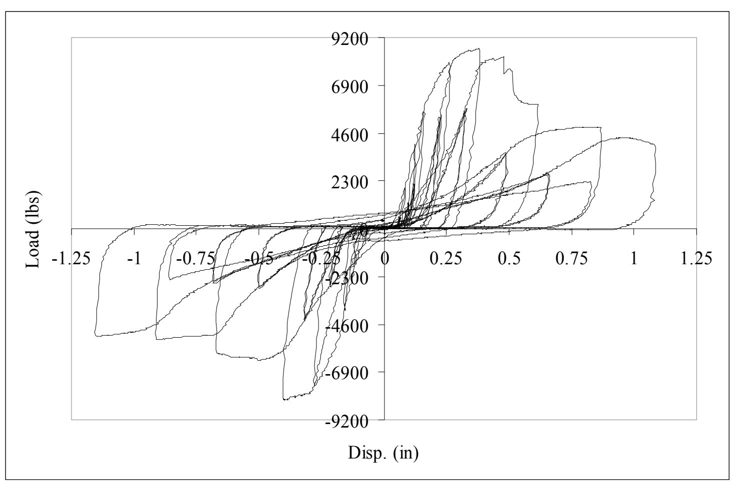

Figure 4.26: Typical load-deflection plot. 461R5C Series.

Three-bolt, two-row connections were exposed to a displacement controlled cyclic protocol as described in Section 3.5.1, where $\Delta = 0.51$ in.. In most of the connections tested there was multiple hinge formations in all bolts, consistent with mode IV yield, yet it should be noted that several connections displayed a range of yield modes between mode III and mode IV. The failure mode for all specimens was splitting through the centerline of the bolt rows on one of the members, or opposite rows on each member (Figure 4.27). A typical load-deflection plot with indication of ductile failure is shown in Figure 4.28.

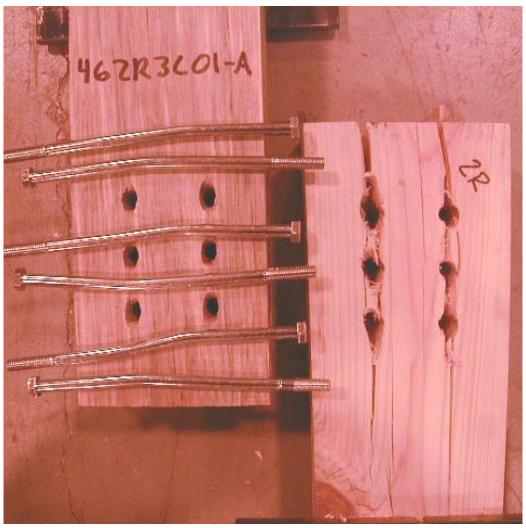

Figure 4.27: Photograph of typical 462R3C Series failure.

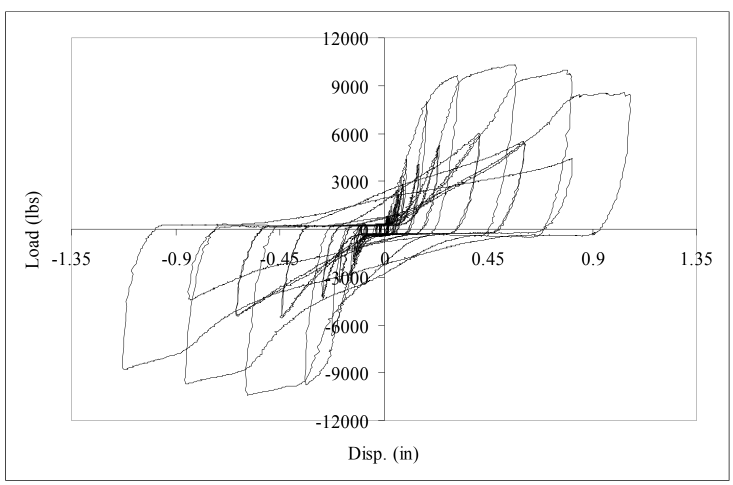

Figure 4.28: Typical load-deflection plot. 462R3C Series.

Five-bolt, two-row connections were exposed to a displacement controlled cyclic protocol as described in Section 3.5.1, where $\Delta = 0.46$ in. Typically, a specimen within this series was observed to have yield modes that ranged between mode III and mode IV. The dominant mode of failure was splitting through the centerline of the bolt rows (Figure 4.29). A typical load-deflection plot with indication of brittle failure is shown in Figure 4.30.

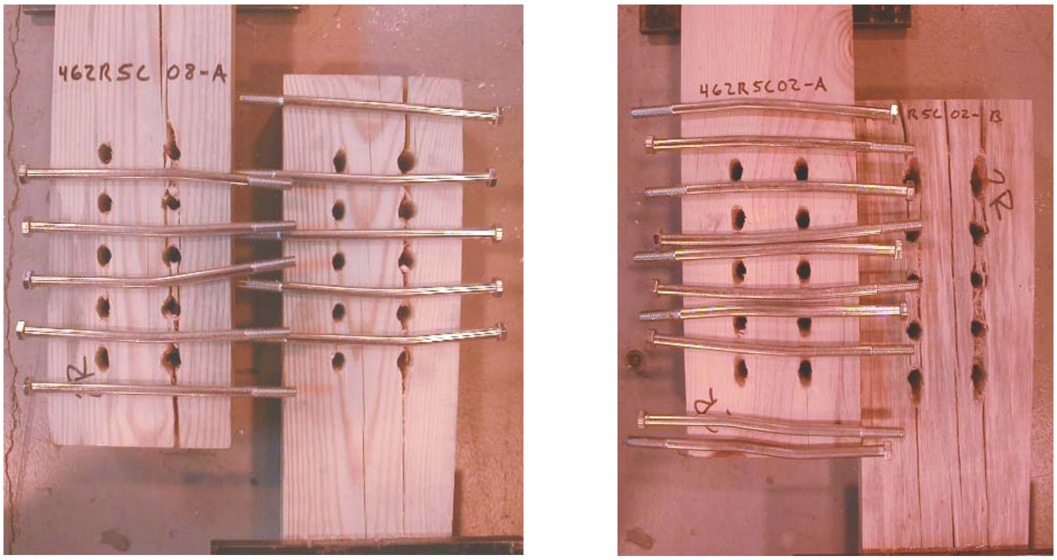

Figure 4.29: Photograph of typical 462R5C Series failure.

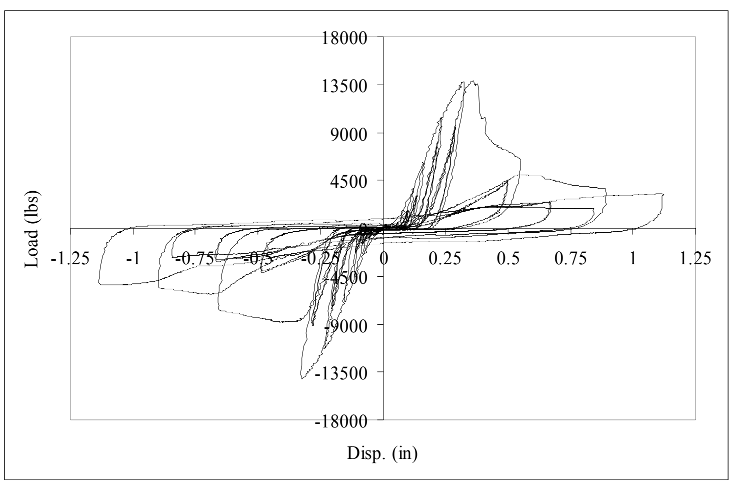

Figure 4.30: Typical load-deflection plot. 462R5C Series.

Connection and member properties for the 46 Series, constructed of 4 in. x 6 in. Southern Yellow Pine members and 3/8 in. diameter bolts, can be found in Table 4.11 and Table 4.12. Results indicate that the prediction of a mode IV yielding mechanism, using the Yield Limit Model, was accurate for most connection configurations, although a range of yield modes was evident in a significant portion of the multiple-bolt connection tests. It appeared that the bolts would yield by migrating through the yield modes from mode II to mode IV. In connection with a mixed mode yield form, the specimen failed due to splitting before all of the bolts could yield in the highest mode. Had the spacing between bolts been larger, the connections with mixed mode yield may have reached a complete mode IV yield condition.

Bolted connections within this series exhibited both ductile and brittle failure mechanisms. Load-deflection plots of single-bolt connections showed a significant non-linear region, due to the plastic hinge formations within the bolt. Three-bolt connections were typically mixed between ductile and brittle failure and analyzed accordingly. Five-bolt connections typically failed in a brittle manner and had indication of mixed mode yield.

Table 4.11: 46 Series cyclic connection properties. Ten replications per series unless otherwise noted.

	461R1C Series		461R3C Series		461R5C Series	
	Mean	**COV (%)**	**Mean**	**COV (%)**	**Mean**	**COV (%)**
Max Load (lbs)	2703.86	14.43	4943.51	9.50	8172.79	6.11
@ Displacement (in)	1.93	6.37	0.50	38.15	0.31	16.83
Load/Bolt (lbs)	2703.86		1647.84		1634.56	
Failure Load (lbs)	2163.09	14.43	3954.81	9.50	6538.23	6.11
@ Displacement (in)	1.93	6.37	0.80	37.77	0.31	16.69
Load/Bolt (lbs)	2163.09		1318.27		1307.65	
40% Max (lbs)	1081.55	14.43	1977.40	9.50	3269.12	6.11
@ Displacement (in)	0.17	18.63	0.13	7.08	0.13	10.75
E.E.P. Yield (lbs)	2221.53	11.81	4557.58	9.76	7344.15	7.71
@ Displacement (in)	0.29	18.88	0.24	11.49	0.22	13.92
Load/Bolt (lbs)	2221.53		1519.19		1468.83	
5% Offset (lbs)	1417.87	9.56	4033.37	22.37	7469.21	9.48
@ Displacement (in)	0.22	11.03	0.29	31.36	0.27	20.15
Load/Bolt (lbs)	1417.87		1344.46		1493.84	
Elastic Stiff. (lb/in)	9595.11	16.21	25788.18	22.86	42656.11	19.09
E.E.P. Energy (lb*in)	3908.03	14.76	3014.46	50.64	1350.85	26.41
Ductility Ratio	6.87	14.14	3.51	41.53	1.46	12.70

	462R3C Series		462R5C Series	
	Mean	**COV (%)**	**Mean**	**COV (%)**
Max Load (lbs)	10286.57	8.44	15346.02	9.76
@ Displacement (in)	0.67	32.19	0.37	20.21
Load/Bolt (lbs)	1714.43		1534.60	
Failure Load (lbs)	8229.26	8.44	12276.82	9.76
@ Displacement (in)	0.88	33.68	0.42	35.66
Load/Bolt (lbs)	1371.54		1227.68	
40% Max (lbs)	4114.63	8.44	6138.41	9.76
@ Displacement (in)	0.15	8.45	0.14	9.22
E.E.P. Yield (lbs)	9473.55	7.78	14131.05	11.61
@ Displacement (in)	0.29	13.33	0.27	10.28
Load/Bolt (lbs)	1578.93		1413.10	
5% Offset (lbs)	7875.87	5.94	14568.12	11.56
@ Displacement (in)	0.28	18.65	0.33	20.96
Load/Bolt (lbs)	1312.65		1456.81	
Elastic Stiff. (lb/in)	41433.07	20.26	56237.49	14.04
E.E.P. Energy (lb*in)	6893.94	42.22	3960.38	61.27
Ductility Ratio	3.12	33.22	1.54	28.69

E.E.P. Yield: Equivalent Elastic-Plastic Yield

Table 4.12: 46 Series cyclic member properties. Ten replications per series unless otherwise noted.

	461R1C Series		461R3C Series		461R5C Series	
Member A	**Mean**	**COV (%)**	**Mean**	**COV (%)**	**Mean**	**COV (%)**
M.C. (%)	15.16	7.30	15.53	7.39	16.09	4.64
Specific Gravity	0.50	23.23	0.51	12.81	0.58	11.72
D.E. 5% Yield (psi)	4952.58	22.08	4482.34	13.72	5238.23	15.68
D.E. Capacity (psi)	5435.11	23.16	4874.24	11.55	5719.21	15.35
Member B						
M.C. (%)	16.18	7.00	15.79	16.87	15.10	9.85
Specific Gravity	0.51	21.52	0.50	15.54	0.53	16.14
D.E. 5% Yield (psi)	4573.19	19.51	4478.36	10.49	5087.61	14.49
D.E. Capacity (psi)	4989.09	18.68	4779.96	11.29	5417.43	15.65

	462R3C Series		462R5C Series	
Member A	**Mean**	**COV (%)**	**Mean**	**COV (%)**
M.C. (%)	15.82	10.47	15.83	13.89
Specific Gravity	0.51	13.23	0.57	17.91
D.E. 5% Yield (psi)	4880.45	16.12	5044.78	26.61
D.E. Capacity (psi)	5285.47	14.99	5425.52	24.32
Member B				
M.C. (%)	16.13	14.27	15.01	9.39
Specific Gravity	0.50	10.74	0.57	20.13
D.E. 5% Yield (psi)	5038.91	15.57	4889.06	23.83
D.E. Capacity (psi)	5349.20	14.87	5325.30	22.17

D.E.: Dowel Embedment Test Data

4.5 – Mode IV Yield (1/2" Bolts)

Tested connections corresponding to yield mode IV were constructed with 4 in. x 6 in. Southern Yellow Pine and 1/2 in. diameter bolts. Further information concerning geometry and test replication can be found in Tables 3.1 and 3.2.

4.5.1 – Monotonic Test Results

Single-bolt connections were tested in tension and displaced to the limits of the testing machine and test fixture. The three specimens tested were observed to have two significant hinge formations in the bolt, corresponding to yield mode IV. Failure could not be attained due to the displacement limitations of the equipment.

Five-bolt, one-row connections were tested in compression until failure. The three specimens were observed to have higher than expected load carrying capacity beyond max load due to confinement of split propagation by the fixture securing plate and lag screws. The specimens were observed to have two hinge formations in all bolts, corresponding to yield mode IV. Splitting of the timber member through the bolt row centerline corresponded to failure but, as noted, strength loss was not catastrophic.

Connection and member properties are shown in Tables 4.13 and 4.14.

Table 4.13: 4X Series monotonic connection properties. Three replications per series unless otherwise noted.

	4X1R1M Series		4X1R5M Series	
	Mean	**COV (%)**	**Mean**	**COV (%)**
Max Load (lbs)	3051.70	1.25	8213.45	9.83
@ Displacement (in)	1.53	4.38	0.51	6.35
Load/Bolt (lbs)	3051.70		1642.69	
Failure Load (lbs)	3014.52	3.16	7061.34	4.98
@ Displacement (in)	1.55	2.27	0.73	18.56
Load/Bolt (lbs)	3014.52		1412.27	
40% Max (lbs)	1201.73	0.79	3224.24	10.06
@ Displacement (in)	0.21	7.38	0.18	18.60
E.E.P. Yield (lbs)	2597.81	1.18	7655.79	9.22
@ Displacement (in)	0.36	5.79	0.33	17.13
Load/Bolt (lbs)	2597.81		1531.16	
5% Offset (lbs)	1659.73	4.62	6256.36	17.33
@ Displacement (in)	0.29	4.98	0.31	22.72
Load/Bolt (lbs)	1659.73		1251.27	
Elastic Stiff. (lb/in)	9082.67	8.08	29384.86	7.91
E.E.P. Energy (lb*in)	3469.42	3.89	4134.54	29.16
Ductility Ratio	4.29	5.56	2.26	20.93

E.E.P. Yield: Equivalent Energy Elastic-Plastic Yield
E.E.P. Energy: Equivalent Elastic-Plastic Energy

Table 4.14: 4X Series monotonic member properties. Three replications per series unless otherwise noted.

	4X1R1M Series		4X1R5M Series	
Member A	**Mean**	**COV (%)**	**Mean**	**COV (%)**
M.C. (%)	15.01	3.12	14.60	19.48
Specific Gravity	0.46	7.58	0.41	6.45
D.E. 5% Yield (psi)	3915.67	4.33	3996.88	21.87
D.E. Capacity (psi)	4030.35	3.67	4331.05	17.88
Member B				
M.C. (%)	16.09	6.11	14.61	23.00
Specific Gravity	0.43	4.80	0.42	6.30
D.E. 5% Yield (psi)	3830.60	10.74	4321.02	23.19
D.E. Capacity (psi)	4171.32	10.90	4569.17	18.46

D.E.: Dowel Embeddment Test Data

4.5.2 – Cyclic Test Results

Single-bolt connections were exposed to a displacement controlled cyclic protocol as described in Section 3.5.1, where $\Delta = 0.56$ in.. In all tests there were two hinge formations within the bolt, typical of mode IV yield (Figure 4.31). Generally, the connection did not exhibit strength loss even after 1.8 in. of relative displacement (Figure 4.32).

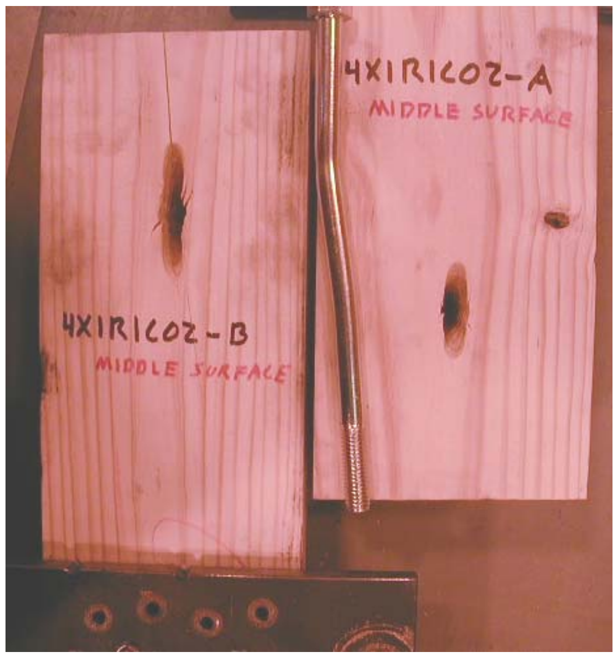

Figure 4.31: Photograph of typical 4X1R1C Series yield.

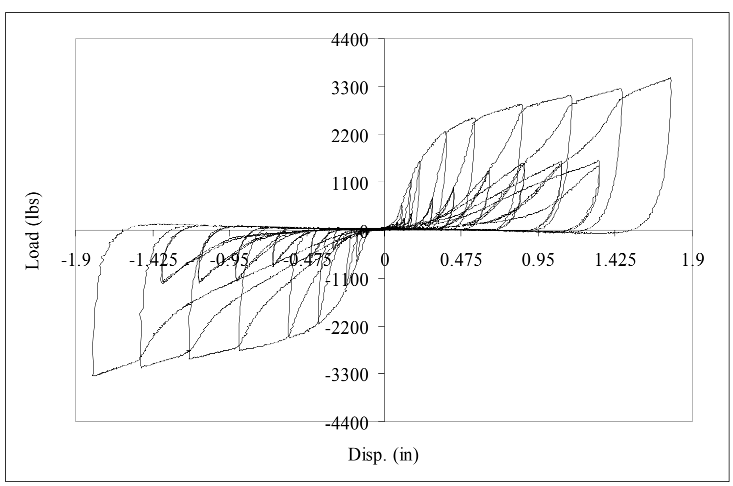

Figure 4.32: Typical load-deflection plot. 4X1R1C Series.

Three-bolt, one-row connections were exposed to a displacement controlled cyclic protocol as described in Section 3.5.1, where $\Delta = 0.56$ in. All connections exhibited mode III yield characterized by the single hinge formed in each bolt. The dominant failure mode was splitting of one member through the centerline of the bolt row (Figure 4.33). A typical load-deflection plot with indication of brittle failure is shown in Figure 4.34.

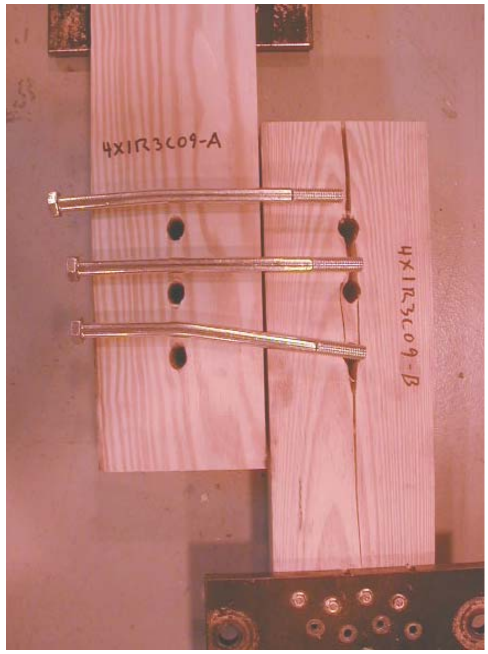

Figure 4.33: Photograph of typical 4X1R3C Series yield.

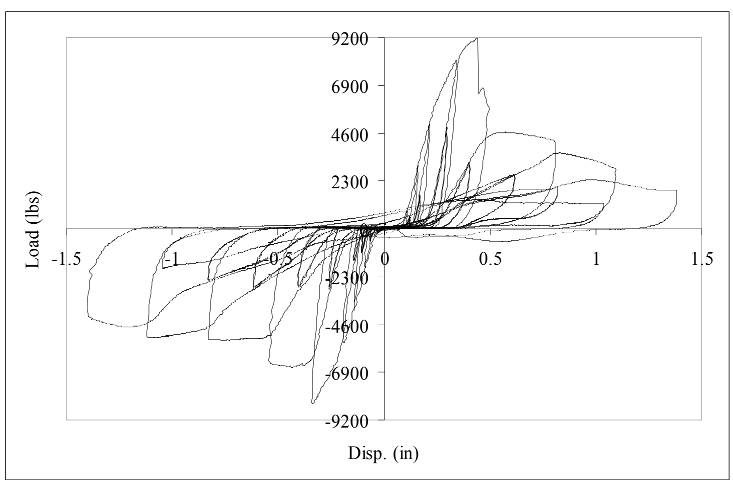

Figure 4.34: Typical load-deflection plot. 4X1R3C Series.

Five-bolt, one-row connections were exposed to a displacement controlled cyclic protocol as described in Section 3.5.1, where $\Delta = 0.56$ in.. All specimens within this series had yield modes that ranged between mode II and mode III on a bolt-by-bolt basis. In general mode II yield was the dominant yielding mechanism. Failure occurred by way of splitting through the centerline of the bolt row (Figure 4.35). A typical load-deflection plot with indication of brittle failure is shown in Figure 4.36.

Figure 4.35: Photograph of typical 4X1R5C Series yield.

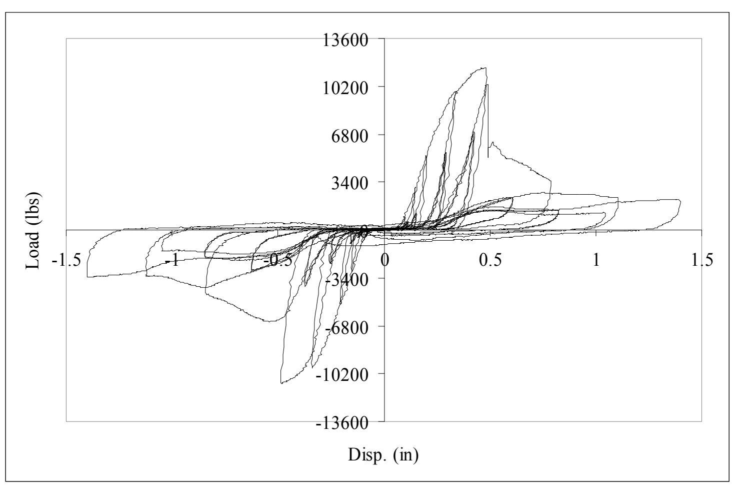

Figure 4.36: Typical load-deflection plot. 4X1R5C Series.

Connection and member properties for the 4X Series, constructed of 4 in. x 6 in. Southern Yellow Pine members and 1/2 in. diameter bolts, can be found in Tables 4.15 and 4.16. Results indicate that the prediction of a mode IV yielding mechanism, using the Yield Limit Model, was accurate only for single-bolt connections. Multiple-bolt connections were typically mixed mode and did not include mode IV yield.

Bolted connections within this series typically exhibited a brittle failure mechanism. Load-deflection plots of single-bolt connections showed a significant non-linear region due to the plastic hinge formations within the bolt. Three-bolt and five-bolt connections typically failed in a brittle manner and exhibited mixed mode yield.

Table 4.15: 4X Series cyclic connection properties. Ten replications per series unless otherwise noted.

	4X1R1C Series*		**4X1R3C Series***		**4X1R5C Series**	
	Mean	**COV (%)**	**Mean**	**COV (%)**	**Mean**	**COV (%)**
Max Load (lbs)	3404.71	13.86	6550.19	16.60	9994.77	15.24
@ Displacement (in)	1.65	18.18	0.41	16.75	0.35	16.17
Load/Bolt (lbs)	3404.71		2183.40		1998.95	
Failure Load (lbs)	2723.77	13.86	5240.15	16.60	7995.81	15.24
@ Displacement (in)	1.72	5.44	0.41	16.75	0.35	16.19
Load/Bolt (lbs)	2723.77		1746.72		1599.16	
40% Max (lbs)	1361.89	13.86	2620.08	16.60	3997.91	15.24
@ Displacement (in)	0.20	6.81	0.17	7.82	0.17	10.78
E.E.P. Yield (lbs)	2963.07	10.86	5665.50	15.53	8639.15	15.42
@ Displacement (in)	0.35	8.41	0.29	12.82	0.27	13.45
Load/Bolt (lbs)	2963.07		1888.50		1727.83	
5% Offset (lbs)	1968.02	19.16	5804.77	21.11	9205.83	13.82
@ Displacement (in)	0.38	67.90	0.33	10.40	0.31	13.79
Load/Bolt (lbs)	1968.02		1934.92		1841.17	
Elastic Stiff. (lb/in)	11390.80	20.05	27407.45	26.10	46904.99	30.76
E.E.P. Energy (lb*in)	4464.02	13.58	1298.97	30.85	1531.48	32.88
Ductility Ratio	5.04	10.81	1.41	8.04	1.30	7.90

* Nine replications
E.E.P. Yield: Equivalent Elastic-Plastic Yield
E.E.P. Energy: Equivalent Elastic-Plastic Energy

Table 4.16: 4X Series cyclic member properties. Ten replications per series unless otherwise noted.

	4X1R1C Series*		4X1R3C Series*		4X1R5C Series	
Member A	**Mean**	**COV (%)**	**Mean**	**COV (%)**	**Mean**	**COV (%)**
M.C. (%)	14.70	10.69	14.49	8.29	13.50	8.48
Specific Gravity	0.49	15.62	0.48	16.57	0.49	13.82
D.E. 5% Yield (psi)	4642.42	22.37	4446.13	19.69	4681.93	17.43
D.E. Capacity (psi)	4764.97	21.63	4670.14	18.43	4822.31	16.14
Member B						
M.C. (%)	14.52	7.55	14.15	8.96	13.94	9.09
Specific Gravity	0.46	10.76	0.47	14.18	0.52	15.58
D.E. 5% Yield (psi)	4472.74	14.04	4545.01	19.39	4638.72	13.47
D.E. Capacity (psi)	4683.90	15.87	4682.78	19.21	4825.16	14.44

* Nine replications
D.E.: Dowel Embedment Test Data

4.6 – Group Action Affects

Up to this point, results have been presented in a series by series manner in order to separate all of the various tables, figures, and photographs. This section specifically deals with the group action affects that were both predicted and based on testing. Results and discussion concerning group action is based on Lantos model predictions and tested performance indicators such as connection capacity, 5% offset yield strength, and ductility ratio. Within the various plots relating to group action, mean single and multiple-bolt, single-row, values are connected by a dashed line as well as mean values for multiple-bolt, multiple-row connections. These lines are drawn to give the reader easier visualization and are not meant to indicate continuity. The number of bolts per row must be an integer and this research did not test two and four-bolt configurations. To give an indication of the distribution of data around the mean, range bars are shown indicating the maximum and minimum values for a particular bolted configuration.

4.6.1 – Lantos Model Predictions

The Lantos model predicts very little reduction in proportional limit strength due to group action over the range of connection geometries tested in this research (See Table 4.17). Lantos model predictions for the group action factor were based on the equation format shown in Equation 2.5 from the 1997 NDS. Values for initial stiffness, or load/slip modulus, γ, are given in the 1997 NDS and were used throughout this research. Because it is not immediately apparent, it should be noted that the load/slip modulus recommendations are based on double-shear bolted connections and do not necessarily represent an accurate approximation of the single-shear load/slip modulus (See Table 4.18).

Table 4.17: Lantos model prediction of group action factor for tested connections

# of Rows	# Bolts per Row	Lantos Model Prediction of GAF			
		2X Series	ST Series	46 Series	4X Series
1	1	1.00	1.00	1.00	1.00
1	3	1.00	1.00	1.00	1.00
1	5	0.98	0.99	1.00	0.99
2	3	0.99	0.99	1.00	
2	5	0.96	0.97	0.99	

2X: (2) 2x6 with 1/2" dia. bolts.
ST: 4x6, 1/4" steel plate, and 3/8" dia. bolts.
46: (2) 4x6 with 3/8" dia. bolts.
4X: (2) 4x6 with 1/2" dia. bolts.

Table 4.18: Initial stiffness values; tested and based on 1997 NDS specifications.

	Single-bolt Initial Stiffness	
	Tested Mean (lb/in)	1997 NDS (lb/in)
2X Series	10001.72	63639.61
ST Series	19770.49	62002.71
46 Series	9595.11	41335.14
4X Series	11390.80	63639.61

The effect of initial stiffness difference between 1997 NDS Specifications and single-shear single-bolt tested values on the Lantos model prediction of group action, warrants discussion. Simply stated the stiffer a connection is, the greater the group action factor as predicted at a proportional limit strength level. Assuming a larger load/slip modulus than is actually provided by single-shear bolted connections makes the group action factor a very conservative estimate. Utilizing the initial stiffness values from single-shear, single-bolt connection tests reported in this thesis in conjunction with the Lantos model, generates a prediction of group action that is effectively nonexistent at proportional limit strength levels, for all tested configurations.

4.6.2 – Ductility Ratio

As a precursor to discussion of observed trends in the group action factor based on tested strength levels, it is important to begin with trends noted in the ductility ratio. Defined as the displacement at failure divided by the displacement at yield (as defined in

Figure 3.13), the ductility ratio is viewed as a comparative variable that gives some indication of the non-linear response of the connection.

To observe the trends in each of the connection configurations, ductility ratio data has been normalized so that the mean normalized ductility ratio for single-bolt configurations is equal to 1.00. Ductility ratio and normalized ductility ratio data can be found in Tables 4.19, 4.21, 4.23, and 4.25 for each respective test series. Plots concerning normalized ductility ratio data are shown in Figures 4.37, 4.38, 4.39, and 4.40. To make inferences about the relationship between different bolt configurations within each test series it is assumed that data is normally distributed about the mean and population variances are equal. Two-sample t-tests are used to test the null hypothesis that any two populations means are equal, using a level of significance, α, equal to 0.05. Decisions concerning the difference between two means, and t-statistics, can be found in Table 4.20, 4.22, 4.24, and 4.26.

Table 4.19: Tested and normalized ductility ratio data, 2X Series.

Test Ductility Ratio

Specimen	2X1R1C	2X1R3C	2X1R5C	2X2R3C	2X2R5C
Spec 1	2.13	1.31	1.23	1.27	1.21
Spec 2	2.03	1.23	1.18	1.52	1.16
Spec 3	2.68	1.37	1.29	1.46	1.26
Spec 4	1.74	1.30	1.34	1.50	1.51
Spec 5	2.35	1.60	1.13	1.75	1.16
Spec 6	2.20	1.32	1.22	1.77	1.38
Spec 7	2.51	1.28	1.29	1.24	1.33
Spec 8	3.20	1.30	1.28	1.40	1.21
Spec 9	1.62	1.19	1.27	1.35	1.33
Spec 10	2.06	1.39	1.25	1.18	1.14
Mean	2.25	1.33	1.25	1.44	1.27

Normalized Ductility Ratio Data

Specimen	2X1R1C	2X1R3C	2X1R5C	2X2R3C	2X2R5C
Spec 1	0.95	0.58	0.55	0.57	0.54
Spec 2	0.90	0.54	0.52	0.68	0.52
Spec 3	1.19	0.61	0.57	0.65	0.56
Spec 4	0.77	0.58	0.59	0.67	0.67
Spec 5	1.04	0.71	0.50	0.78	0.51
Spec 6	0.98	0.59	0.54	0.78	0.61
Spec 7	1.11	0.57	0.57	0.55	0.59
Spec 8	1.42	0.58	0.57	0.62	0.54
Spec 9	0.72	0.53	0.56	0.60	0.59
Spec 10	0.92	0.62	0.56	0.52	0.50
Mean	1.00	0.59	0.55	0.64	0.56
StDev	0.21	0.05	0.03	0.09	0.05

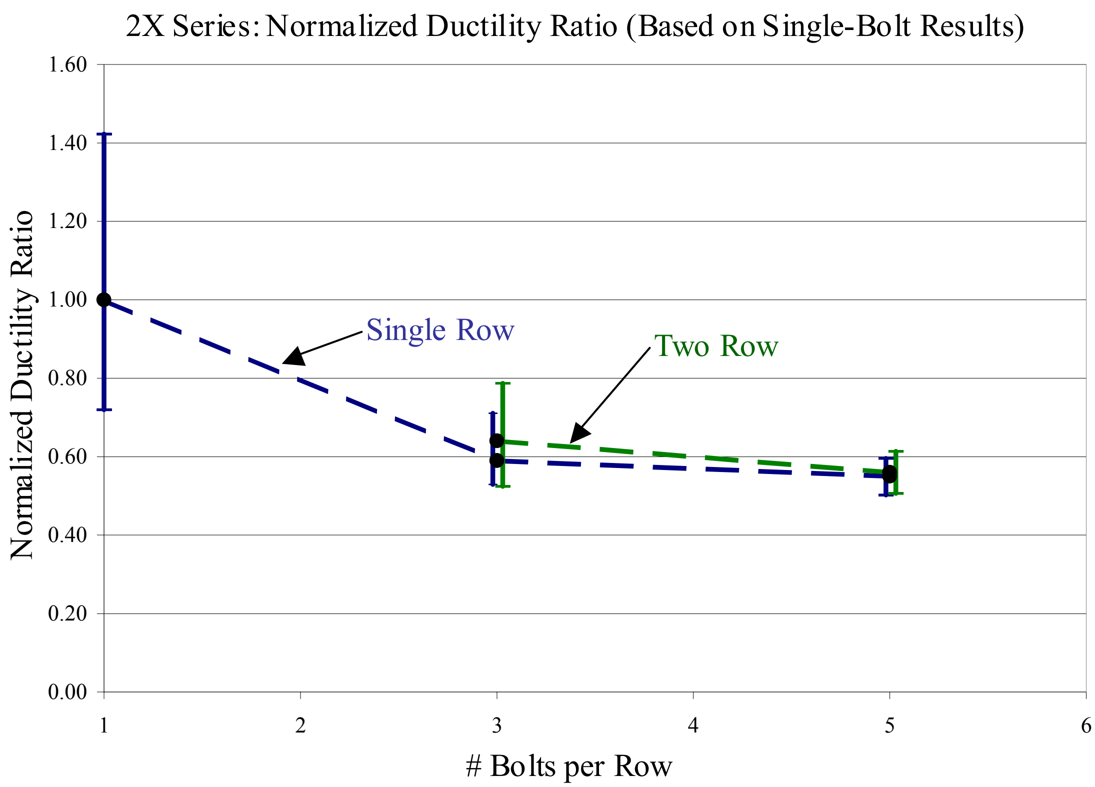

Figure 4.37: Normalized Ductility Ratio, 2X Series.

Table 4.20: Inferences concerning means, 2X Series.

t-statistic for small sample test concerning difference between two means.

	2X1R1C	2X1R3C	2X1R5C	2X2R3C	2X2R5C
2X1R1C	0				
2X1R3C	6.16	0			
2X1R5C	6.81	1.96	0		
2X2R3C	5.08	-1.62	-2.95	0	
2X2R5C	6.52	1.12	-0.48	2.37	0

$t_{\alpha/2}$ = 2.11 (Level α = 0.05 and 18 dof's)

Decision concerning difference between two means

	2X1R1C	2X1R3C	2X1R5C	2X2R3C	2X2R5C
2X1R1C	0				
2X1R3C	Reject H_o	0			
2X1R5C	Reject H_o	C.R. H_o	0		
2X2R3C	Reject H_o	C.R. H_o	Reject H_o	0	
2X2R5C	Reject H_o	C.R. H_o	C.R. H_o	Reject H_o	0

Reject H_o: Reject null hypothesis that means are equal.

C.R. H_o: Cannot reject null hypothesis that means are equal

Table 4.21: Tested and normalized ductility ratio data, ST Series.

Test Ductility Ratio

Specimen	ST1R1C	ST1R3C	ST1R5C	ST2R3C	ST2R5C
Spec 1	5.02	1.96	1.51	2.13	1.38
Spec 2	6.62	3.03	1.41	4.10	1.24
Spec 3	5.77	1.64	1.09	3.99	1.23
Spec 4	4.61	1.65	1.16	1.95	1.19
Spec 5	5.30	4.09	1.60	3.68	1.39
Spec 6	5.10	2.24	1.36	3.73	2.38
Spec 7	4.63	2.75	1.43	4.68	3.17
Spec 8	4.42	4.51	1.36	2.33	1.83
Spec 9	5.19	1.69	1.36	2.99	1.14
Spec 10	5.12	3.98	1.30	4.00	1.36
Mean	5.18	2.76	1.36	3.36	1.63

Normalized Ductility Ratio Data

Specimen	ST1R1C	ST1R3C	ST1R5C	ST2R3C	ST2R5C
Spec 1	0.97	0.38	0.29	0.41	0.27
Spec 2	1.28	0.59	0.27	0.79	0.24
Spec 3	1.11	0.32	0.21	0.77	0.24
Spec 4	0.89	0.32	0.22	0.38	0.23
Spec 5	1.02	0.79	0.31	0.71	0.27
Spec 6	0.98	0.43	0.26	0.72	0.46
Spec 7	0.89	0.53	0.28	0.90	0.61
Spec 8	0.85	0.87	0.26	0.45	0.35
Spec 9	1.00	0.33	0.26	0.58	0.22
Spec 10	0.99	0.77	0.25	0.77	0.26
Mean	1.00	0.53	0.26	0.65	0.32
StDev	0.12	0.21	0.03	0.18	0.13

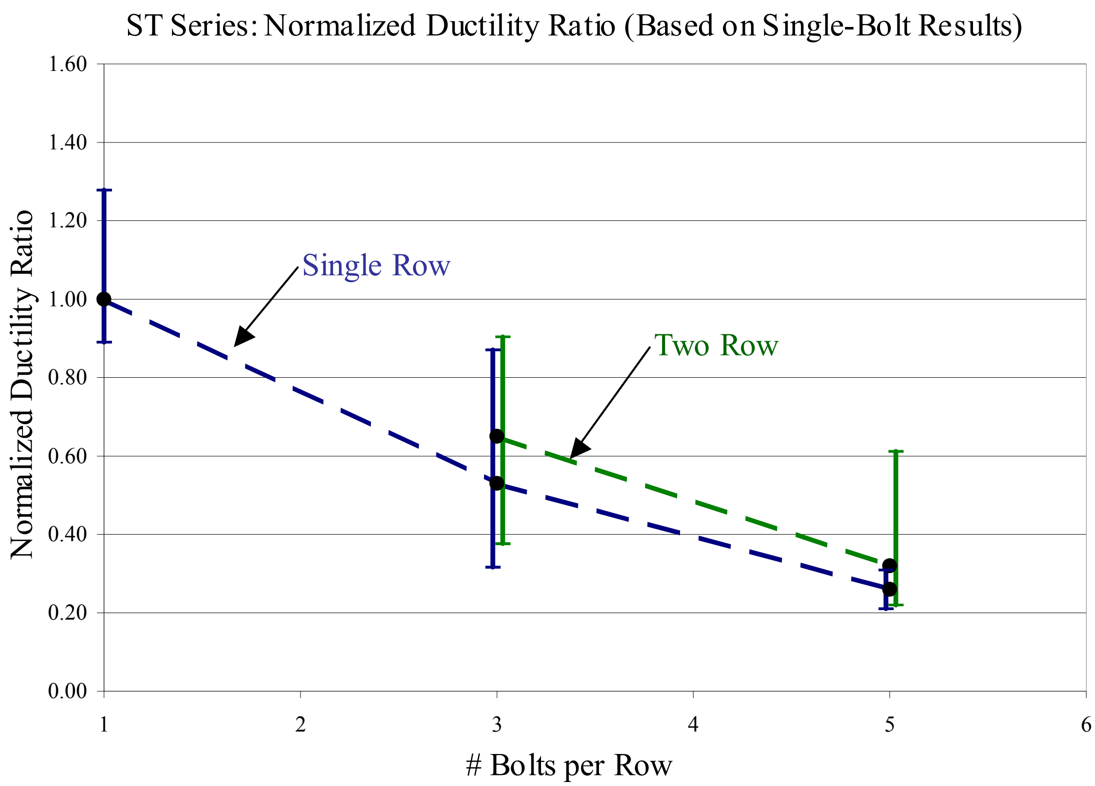

Figure 4.38: Normalized Ductility Ratio, ST Series.

Table 4.22: Inferences concerning means, ST Series.

t-statistic for small sample test concerning difference between two means.

	ST1R1C	ST1R3C	ST1R5C	ST2R3C	ST2R5C
ST1R1C	0				
ST1R3C	6.02	0			
ST1R5C	18.43	3.98	0		
ST2R3C	5.05	-1.31	-6.62	0	
ST2R5C	12.22	2.77	-1.28	4.74	0

$t_{\alpha/2}$ = 2.11 (Level α = 0.05 and 18 dof's)

Decision concerning difference between two means

	ST1R1C	ST1R3C	ST1R5C	ST2R3C	ST2R5C
ST1R1C	0				
ST1R3C	Reject H_o	0			
ST1R5C	Reject H_o	Reject H_o	0		
ST2R3C	Reject H_o	C.R. H_o	Reject H_o	0	
ST2R5C	Reject H_o	Reject H_o	C.R. H_o	Reject H_o	0

Reject H_o: Reject null hypothesis that means are equal.

C.R. H_o: Cannot reject null hypothesis that means are equal

Table 4.23: Tested and normalized ductility ratio data, 46 Series.

Test Ductility Ratio

Specimen	461R1C	461R3C	461R5C	462R3C	462R5C
Spec 1	4.63	3.40	1.51	1.47	1.50
Spec 2	7.73	1.95	1.60	2.15	2.69
Spec 3	7.58	6.05	1.20	3.08	1.74
Spec 4	6.19	2.18	1.58	5.04	1.31
Spec 5	7.54	4.87	1.80	3.11	1.34
Spec 6	7.68	1.59	1.36	3.59	1.40
Spec 7	7.28	4.23	1.39	3.72	1.65
Spec 8	6.56	4.49	1.21	3.69	1.26
Spec 9	7.20	2.39	1.53	1.97	1.14
Spec 10	6.30	3.99	1.40	3.33	1.38
Mean	6.87	3.51	1.46	3.12	1.54

Normalized Ductility Ratio Data

Specimen	461R1C	461R3C	461R5C	462R3C	462R5C
Spec 1	0.67	0.49	0.22	0.21	0.22
Spec 2	1.13	0.28	0.23	0.31	0.39
Spec 3	1.10	0.88	0.17	0.45	0.25
Spec 4	0.90	0.32	0.23	0.73	0.19
Spec 5	1.10	0.71	0.26	0.45	0.19
Spec 6	1.12	0.23	0.20	0.52	0.20
Spec 7	1.06	0.62	0.20	0.54	0.24
Spec 8	0.95	0.65	0.18	0.54	0.18
Spec 9	1.05	0.35	0.22	0.29	0.17
Spec 10	0.92	0.58	0.20	0.49	0.20
Mean	1.00	0.51	0.21	0.45	0.22
StDev	0.14	0.21	0.03	0.15	0.06

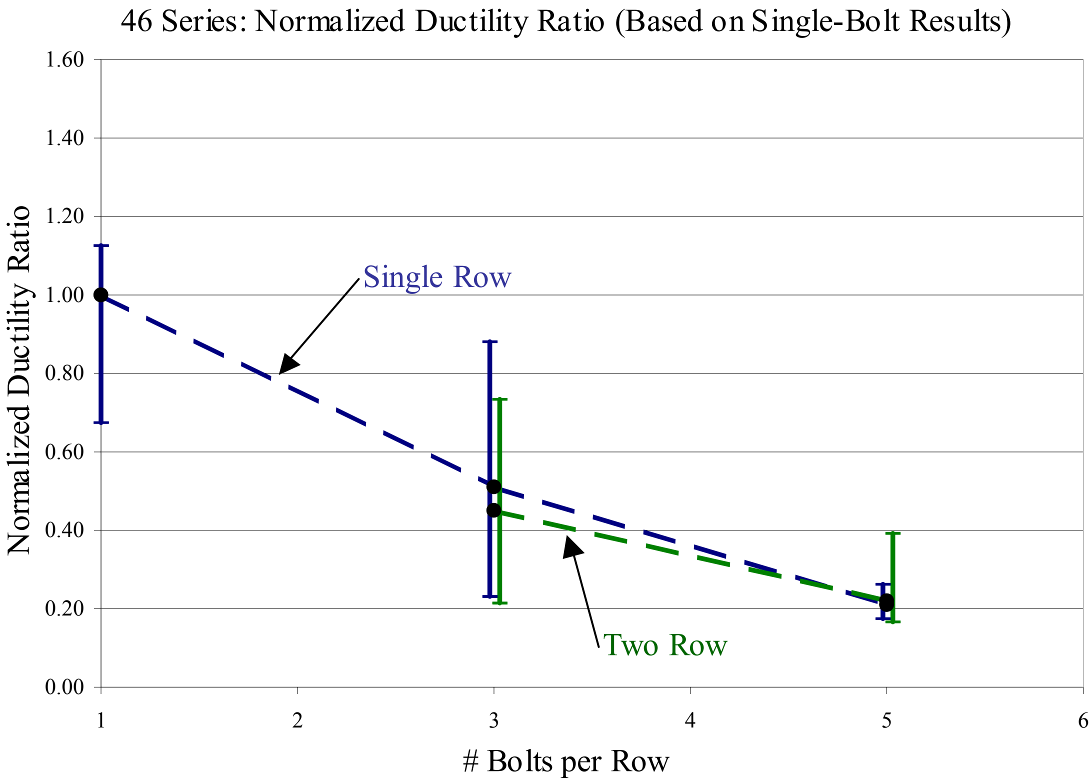

Figure 4.39: Normalized Ductility Ratio, 46 Series.

Table 4.24: Inferences concerning means, 46 Series.

t-statistic for small sample test concerning difference between two means.

	461R1C	461R3C	461R5C	462R3C	462R5C
461R1C	0				
461R3C	6.06	0			
461R5C	17.30	4.42	0		
462R3C	8.36	0.70	-4.99	0	
462R5C	15.78	4.09	-0.56	4.42	0

$t_{\alpha/2}$ = 2.11 (Level α = 0.05 and 18 dof's)

Decision concerning difference between two means

	461R1C	461R3C	461R5C	462R3C	462R5C
461R1C	0				
461R3C	Reject H_o	0			
461R5C	Reject H_o	Reject H_o	0		
462R3C	Reject H_o	C.R. H_o	Reject H_o	0	
462R5C	Reject H_o	Reject H_o	C.R. H_o	Reject H_o	0

Reject H_o: Reject null hypothesis that means are equal.

C.R. H_o: Cannot reject null hypothesis that means are equal

Table 4.25: Tested and normalized ductility ratio data, 4X Series.

Test Ductility Ratio

Specimen	4X1R1C	4X1R3C	4X1R5C
Spec 1	5.77	1.35	1.23
Spec 2	4.93	1.16	1.21
Spec 3	4.74	1.54	1.39
Spec 4	4.82	1.42	1.23
Spec 5		1.44	1.31
Spec 6	4.37	1.50	1.51
Spec 7	6.01	1.50	1.38
Spec 8	4.95	1.37	1.16
Spec 9	5.23	1.42	1.28
Spec 10	4.52		1.29
Mean	5.04	1.41	1.30

Normalized Ductility Ratio Data

Specimen	4X1R1C	4X1R3C	4X1R5C
Spec 1	1.15	0.27	0.24
Spec 2	0.98	0.23	0.24
Spec 3	0.94	0.31	0.28
Spec 4	0.96	0.28	0.25
Spec 5		0.29	0.26
Spec 6	0.87	0.30	0.30
Spec 7	1.19	0.30	0.27
Spec 8	0.98	0.27	0.23
Spec 9	1.04	0.28	0.25
Spec 10	0.90		0.26
Mean	1.00	0.28	0.26
StDev	0.11	0.02	0.02

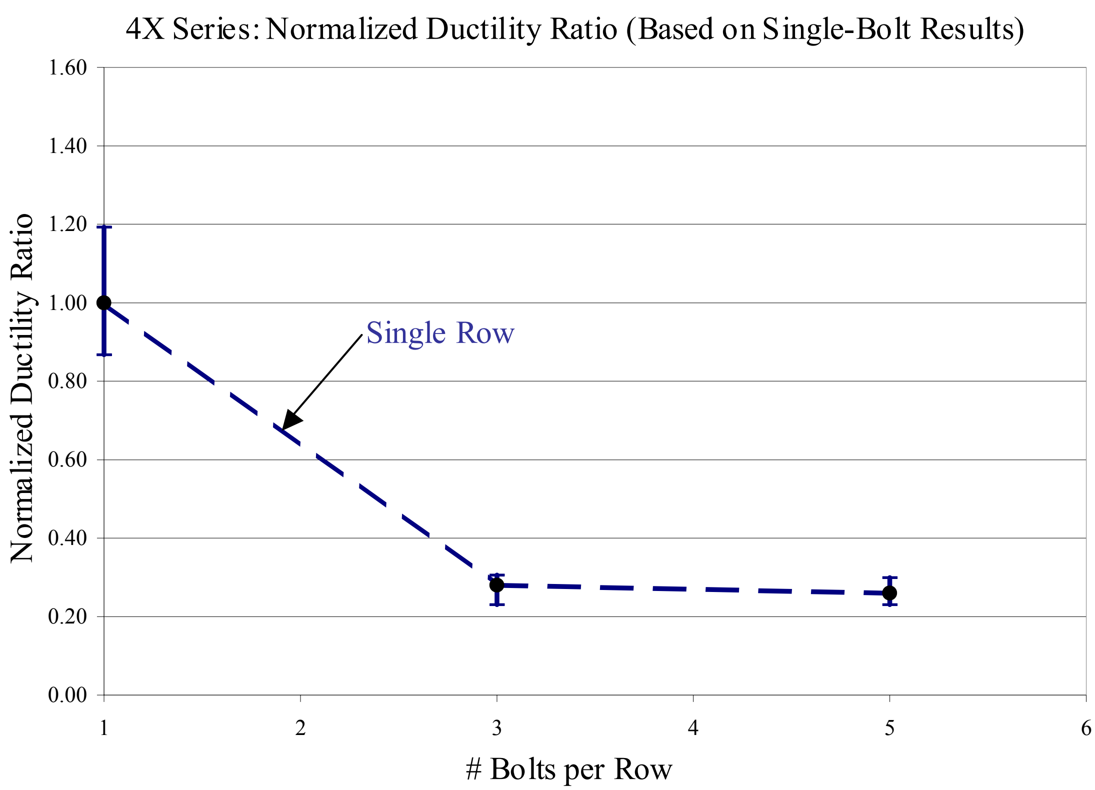

Figure 4.40: Normalized Ductility Ratio, 4X Series.

Table 4.26: Inferences concerning means, 4X Series.

t-statistic for small sample test concerning difference between two means.

	4X1R1C	4X1R3C	4X1R5C
4X1R1C	0		
4X1R3C	19.54	0	
4X1R5C	21.36	2.30	0

$t_{\alpha/2}$ = 2.11 (Level α = 0.05 and 18 dof's)

Decision concerning difference between two means

	4X1R1C	4X1R3C	4X1R5C
4X1R1C	0		
4X1R3C	Reject H_o	0	
4X1R5C	Reject H_o	Reject H_o	0

Reject H_o: Reject null hypothesis that means are equal.

C.R. H_o: Cannot reject null hypothesis that means are equal

Load-deflection plots for all single-bolt connections exposed to cyclic loading show a significantly higher ductility ratio when compared to multiple-bolt connections. Inferences concerning means indicate that, within each test series, the single-bolt normalized ductility ratio is statistically different from all multiple-bolt normalized ductility ratios. This agrees with observations concerning a high degree of inelastic response in single-bolt specimens as compared to multiple-bolt specimens. In the case of the 2X series, it is noted that a brittle failure mechanism controlled but significant inelastic deformation occurred prior to that event.

Results concerning the normalized ductility ratios indicate that for a constant number of bolts per row the observed difference between single and two-row means is not significant. Consequently it cannot be proved that there is not a row interaction in relation to ductility ratios, but it also cannot be disproved at a level of significance, α, equal to 0.05.

Results indicate that the there is a significant difference concerning the mean normalized ductility ratio between connections having three bolts per row and five bolts per row for all configurations except the 2X series. Connection configurations having three-bolts per row within the ST series and the 46 series were mixed between ductile and brittle failure mechanisms while configurations having five-bolts per row had brittle failure mechanisms; based on load-deflection plots.

To summarize, the ability for multiple-bolt connections to sustain substantial load in the post capacity region of displacement is substantially reduced as the number of bolts per row increases.

4.6.3 – 5% Offset Yield Strength

To observe the trends in each of the connection configurations, 5% offset yield strength data has been divided by the total number of bolts, based on the specific connection configuration, and normalized so that the mean normalized 5% offset yield strength for single-bolt configurations is equal to 1.00. This approach is used to determine the group action factor, C_g, as it is shown in Equation 2.1. The 5% offset yield strength data and group action factor data can be found in Tables 4.27, 4.29, 4.31, and 4.33 for each respective test series. Plots concerning the group action factor based on 5% offset yield strength are shown in Figures 4.41, 4.42, 4.43, and 4.44. To make inferences about the relationship between different bolt configurations within each test series it is assumed that data is normally distributed about the mean and population variances are equal. Two-sample t-tests are used to test the null hypothesis that any two population means are equal, using a level of significance, α, equal to 0.05. Decisions concerning the difference between two means, and t-statistics, can be found in Tables 4.28, 4.30, 4.32, and 4.34.

Table 4.27: Test and GAF data at 5% offset yield strength, 2X Series.

Test 5% Offset Yield Strength (lbs.)

Specimen	2X1R1C	2X1R3C	2X1R5C	2X2R3C	2X2R5C
Spec 1	1718.17	4533.58	8078.24	10775.46	20929.54
Spec 2	1390.46	5086.52	8254.32	10513.72	13741.50
Spec 3	2092.54	5354.44	6457.67	9418.02	16350.55
Spec 4	1547.70	5654.59	7106.36	10016.18	13289.17
Spec 5	1305.11	5530.94	9324.70	9550.29	18064.10
Spec 6	1498.74	4793.69	9168.24	11093.42	17455.38
Spec 7	1442.00	5602.23	7362.05	11853.36	15393.39
Spec 8	1711.31	4900.53	8967.36	14320.45	15653.33
Spec 9	1859.22	6202.53	9735.43	11472.52	17751.31
Spec 10	1473.78	4871.01	7325.58	9723.41	12865.69
Mean	1603.90	5253.00	8178.00	10873.68	16149.40

Group Action Factor Data

Specimen	2X1R1C	2X1R3C	2X1R5C	2X2R3C	2X2R5C
Spec 1	1.07	0.94	1.01	1.12	1.30
Spec 2	0.87	1.06	1.03	1.09	0.86
Spec 3	1.30	1.11	0.81	0.98	1.02
Spec 4	0.96	1.18	0.89	1.04	0.83
Spec 5	0.81	1.15	1.16	0.99	1.13
Spec 6	0.93	1.00	1.14	1.15	1.09
Spec 7	0.90	1.16	0.92	1.23	0.96
Spec 8	1.07	1.02	1.12	1.49	0.98
Spec 9	1.16	1.29	1.21	1.19	1.11
Spec 10	0.92	1.01	0.91	1.01	0.80
Mean	1.00	1.09	1.02	1.13	1.01
StDev	0.15	0.11	0.14	0.15	0.16

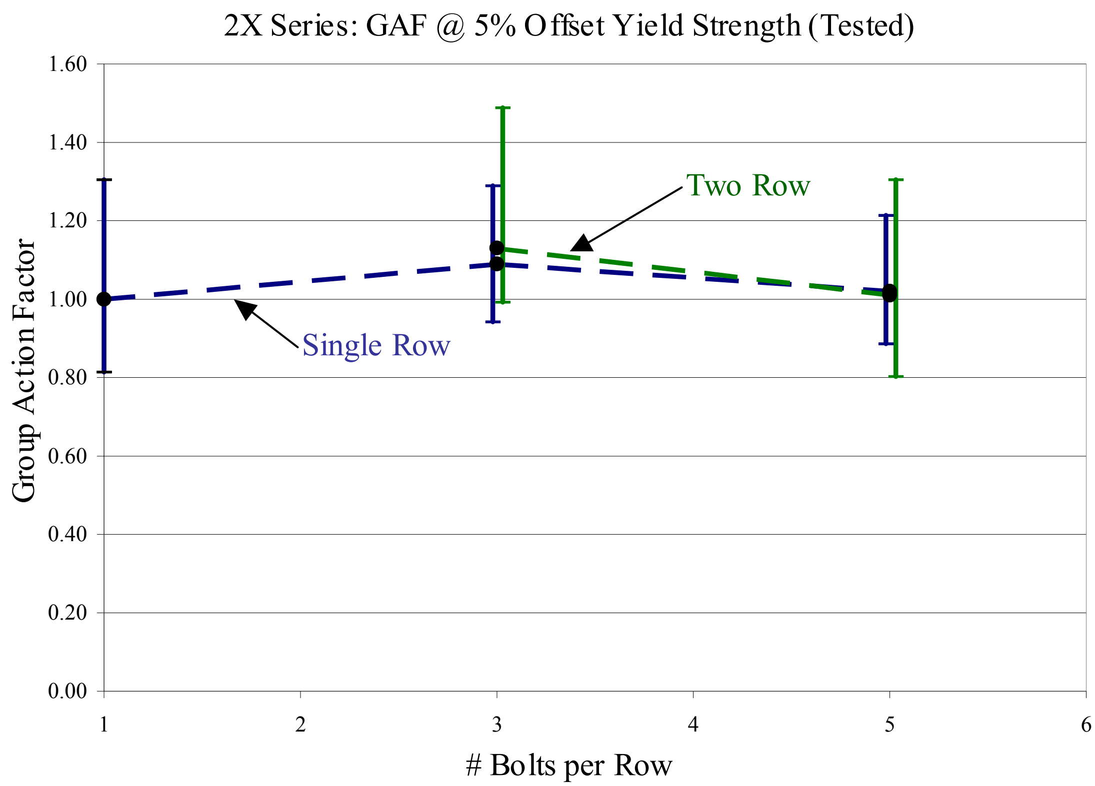

Figure 4.41: Group Action Factor based on 5% offset yield strength, 2X Series.

Table 4.28: Inferences concerning means, 2X Series.

t-statistic for small sample test concerning difference between two means.

	2X1R1C	2X1R3C	2X1R5C	2X2R3C	2X2R5C
2X1R1C	0				
2X1R3C	-1.58	0			
2X1R5C	-0.31	1.32	0		
2X2R3C	-1.92	-0.65	-1.70	0	
2X2R5C	-0.10	1.43	0.20	1.78	0

$t_{\alpha/2}$ = 2.11 (Level α = 0.05 and 18 dof's)

Decision concerning difference between two means

	2X1R1C	2X1R3C	2X1R5C	2X2R3C	2X2R5C
2X1R1C	0				
2X1R3C	C.R. H_o	0			
2X1R5C	C.R. H_o	C.R. H_o	0		
2X2R3C	C.R. H_o	C.R. H_o	C.R. H_o	0	
2X2R5C	C.R. H_o	C.R. H_o	C.R. H_o	C.R. H_o	0

Reject H_o: Reject null hypothesis that means are equal.

C.R. H_o: Cannot reject null hypothesis that means are equal

Table 4.29: Test and GAF data at 5% offset yield strength, ST Series.

Test 5% Offset Yield Strength (lbs.)

Specimen	ST1R1C	ST1R3C	ST1R5C	ST2R3C	ST2R5C
Spec 1	2187.57	5059.03	12482.84	12131.15	18664.47
Spec 2	1843.60	4807.96	8421.55	13292.66	17981.21
Spec 3	1727.11	6192.04	10177.55	14382.24	21169.34
Spec 4	2069.68	5607.58	8864.25	12019.81	18500.19
Spec 5	1898.11	4018.80	8936.96	11521.00	20576.50
Spec 6	2330.10	4352.71	8233.10	10714.10	18586.32
Spec 7	2305.67	5112.59	6598.96	9416.55	15830.84
Spec 8	1999.31	6367.18	12149.75	9925.22	16038.28
Spec 9	1831.22	4508.44	9942.96	12097.20	20046.83
Spec 10	1590.16	5262.53	10236.20	12369.30	19724.26
Mean	1978.25	5128.89	9604.41	11786.92	18711.82

Group Action Factor Data

Specimen	ST1R1C	ST1R3C	ST1R5C	ST2R3C	ST2R5C
Spec 1	1.11	0.85	1.26	1.02	0.94
Spec 2	0.93	0.81	0.85	1.12	0.91
Spec 3	0.87	1.04	1.03	1.21	1.07
Spec 4	1.05	0.94	0.90	1.01	0.94
Spec 5	0.96	0.68	0.90	0.97	1.04
Spec 6	1.18	0.73	0.83	0.90	0.94
Spec 7	1.17	0.86	0.67	0.79	0.80
Spec 8	1.01	1.07	1.23	0.84	0.81
Spec 9	0.93	0.76	1.01	1.02	1.01
Spec 10	0.80	0.89	1.03	1.04	1.00
Mean	1.00	0.86	0.97	0.99	0.95
StDev	0.12	0.13	0.18	0.13	0.09

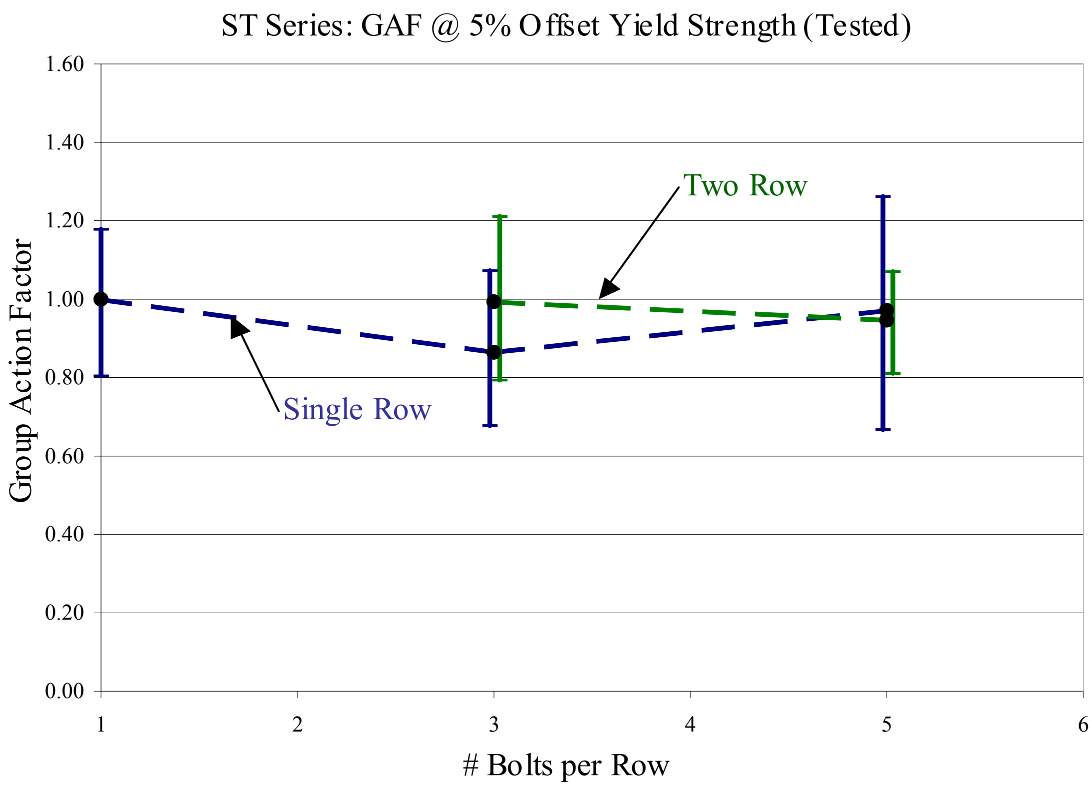

Figure 4.42: Group Action Factor based on 5% offset yield strength, ST Series.

Table 4.30: Inferences concerning means, ST Series.

t-statistic for small sample test concerning difference between two means.

	ST1R1C	ST1R3C	ST1R5C	ST2R3C	ST2R5C
ST1R1C	0				
ST1R3C	2.40	0			
ST1R5C	0.42	-1.52	0		
ST2R3C	0.12	-2.27	-0.32	0	
ST2R5C	1.12	-1.65	0.39	0.97	0

$t_{\alpha/2}$ = 2.11 (Level α = 0.05 and 18 dof's)

Decision concerning difference between two means

	ST1R1C	ST1R3C	ST1R5C	ST2R3C	ST2R5C
ST1R1C	0				
ST1R3C	Reject H_o	0			
ST1R5C	C.R. H_o	C.R. H_o	0		
ST2R3C	C.R. H_o	Reject H_o	C.R. H_o	0	
ST2R5C	C.R. H_o	C.R. H_o	C.R. H_o	C.R. H_o	0

Reject H_o: Reject null hypothesis that means are equal.

C.R. H_o: Cannot reject null hypothesis that means are equal

Table 4.31: Test and GAF data at 5% offset yield strength, 46 Series.

Test 5% Offset Yield Strength (lbs.)

Specimen	461R1C	461R3C	461R5C	462R3C	462R5C
Spec 1	1286.87	4234.66	7820.25	7684.80	13905.41
Spec 2	1512.84	3259.54	7189.25	7203.07	16543.01
Spec 3	1533.52	4528.78	7958.24	8152.77	17209.20
Spec 4	1498.75	3965.43	7409.85	7289.92	16180.79
Spec 5	1390.68	3334.99	7129.28	8261.44	13582.86
Spec 6	1260.37	5185.77	9021.90	7952.28	12525.88
Spec 7	1489.40	5031.26	6468.54	8629.84	15087.09
Spec 8	1432.35	2189.75	7036.96	7506.08	12700.80
Spec 9	1178.92	4508.60	6933.65	8313.73	14978.35
Spec 10	1594.99	4094.91	7724.14	7764.80	12967.80
Mean	1417.87	4033.37	7469.21	7875.87	14568.12

Group Action Factor Data

Specimen	461R1C	461R3C	461R5C	462R3C	462R5C
Spec 1	0.91	1.00	1.10	0.90	0.98
Spec 2	1.07	0.77	1.01	0.85	1.17
Spec 3	1.08	1.06	1.12	0.96	1.21
Spec 4	1.06	0.93	1.05	0.86	1.14
Spec 5	0.98	0.78	1.01	0.97	0.96
Spec 6	0.89	1.22	1.27	0.93	0.88
Spec 7	1.05	1.18	0.91	1.01	1.06
Spec 8	1.01	0.51	0.99	0.88	0.90
Spec 9	0.83	1.06	0.98	0.98	1.06
Spec 10	1.12	0.96	1.09	0.91	0.91
Mean	1.00	0.95	1.05	0.93	1.03
StDev	0.10	0.21	0.10	0.06	0.12

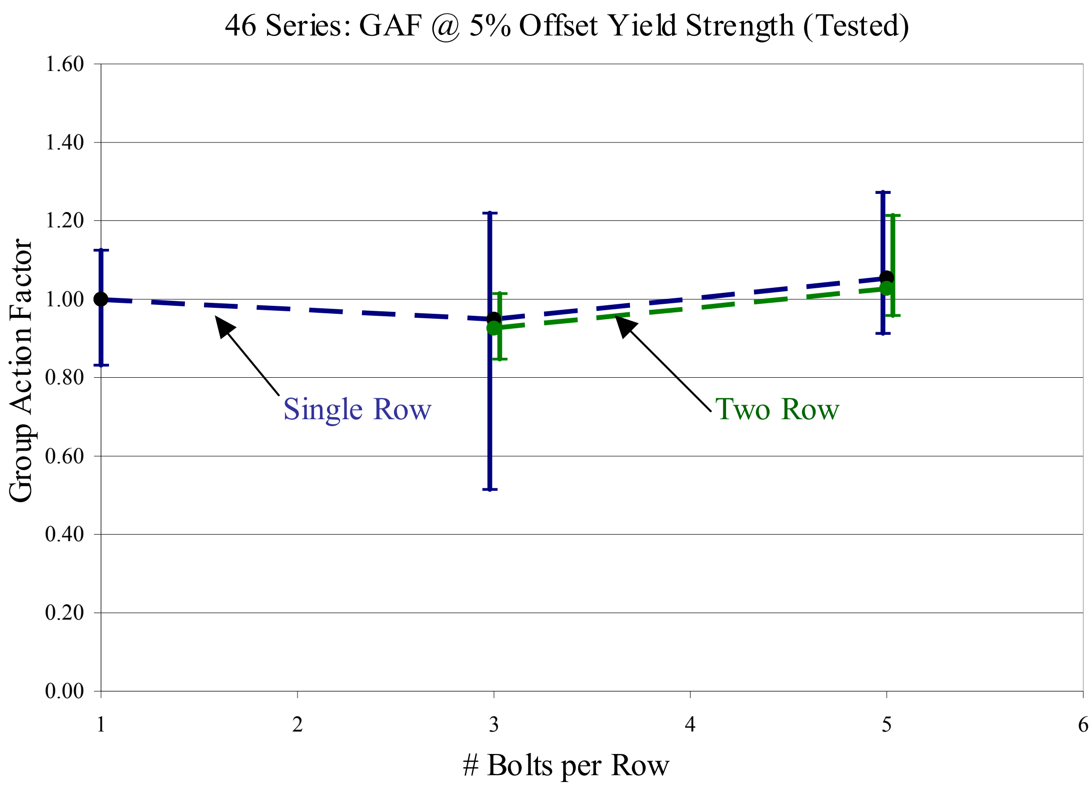

Figure 4.43: Group Action Factor based on 5% offset yield strength, 46 Series.

Table 4.32: Inferences concerning means, 46 Series.

t-statistic for small sample test concerning difference between two means.

	461R1C	461R3C	461R5C	462R3C	462R5C
461R1C	0				
461R3C	0.70	0			
461R5C	-1.23	-1.42	0		
462R3C	2.13	0.32	3.54	0	
462R5C	-0.57	-1.03	0.53	-2.46	0

$t_{\alpha/2}$ = 2.11 (Level α = 0.05 and 18 dof's)

Decision concerning difference between two means

	461R1C	461R3C	461R5C	462R3C	462R5C
461R1C	0				
461R3C	C.R. H_o	0			
461R5C	C.R. H_o	C.R. H_o	0		
462R3C	Reject H_o	C.R. H_o	Reject H_o	0	
462R5C	C.R. H_o	C.R. H_o	C.R. H_o	Reject H_o	0

Reject H_o: Reject null hypothesis that means are equal.

C.R. H_o: Cannot reject null hypothesis that means are equal

Table 4.33: Test and GAF data at 5% offset yield strength, 4X Series.

Test 5% Offset Yield Strength (lbs.)

Specimen	4X1R1C	4X1R3C	4X1R5C
Spec 1	1571.26	5775.89	9308.95
Spec 2	1725.13	4899.30	9659.12
Spec 3	2536.90	4864.17	7477.94
Spec 4	2038.33	5953.65	9909.88
Spec 5		5204.06	9576.72
Spec 6	2408.48	8793.32	9642.58
Spec 7	2264.13	5029.30	11342.36
Spec 8	1582.32	5422.99	9558.75
Spec 9	1567.82	6300.29	6831.23
Spec 10	2017.77		8750.73
Mean	1968.02	5804.77	9205.83

Group Action Factor Data

Specimen	4X1R1C	4X1R3C	4X1R5C
Spec 1	0.80	0.98	0.95
Spec 2	0.88	0.83	0.98
Spec 3	1.29	0.82	0.76
Spec 4	1.04	1.01	1.01
Spec 5		0.88	0.97
Spec 6	1.22	1.49	0.98
Spec 7	1.15	0.85	1.15
Spec 8	0.80	0.92	0.97
Spec 9	0.80	1.07	0.69
Spec 10	1.03		0.89
Mean	1.00	0.98	0.94
StDev	0.19	0.21	0.13

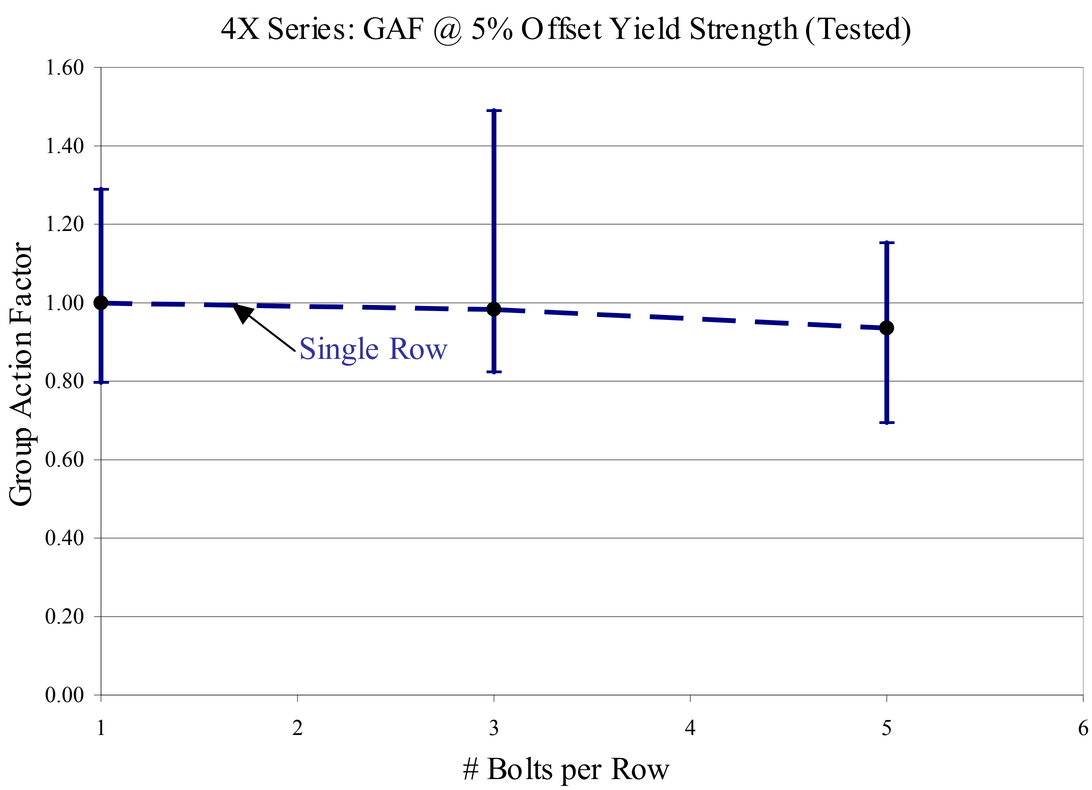

Figure 4.44: Group Action Factor based on 5% offset yield strength, 4X Series.

Table 4.34: Inferences concerning means, 4X Series.

t-statistic for small sample test concerning difference between two means.

	4X1R1C	4X1R3C	4X1R5C
4X1R1C	0		
4X1R3C	0.18	0	
4X1R5C	0.20	0.61	0

$t_{\alpha/2}$ = 2.11 (Level α = 0.05 and 18 dof's)

Decision concerning difference between two means

	4X1R1C	4X1R3C	4X1R5C
4X1R1C	0		
4X1R3C	C.R. H_o	0	
4X1R5C	C.R. H_o	C.R. H_o	0

Reject H_o: Reject null hypothesis that means are equal.
C.R. H_o: Cannot reject null hypothesis that means are equal

Inferences concerning means indicate that, within the 2X and 4X test series, the observed difference between the group action factor based on 5% offset yield strength is not statistically significant for all pair-wise comparisons. Consequently it cannot be proved that a group action affect exists at the 5% offset strength level, but it also cannot be disproved at a level of significance, α, equal to 0.05.

Results indicate that within the ST series, a significant statistical difference exists between single-bolt single-row and three-bolt single-row connections as well as between three-bolt single-row and three-bolt two-row connections. Within the 46 series, a significant statistical difference exists between single-bolt single-row and three-bolt two-row connections as well as between three-bolt two-row and five-bolt two-row connections. However, from a practical standpoint, the GAF could easily be eliminated for design purposes by making a minor adjustment to the single-bolt design values, while maintaining the present safety level for the connection.

The GAF based on 5% offset yield strength may be an inconsistent parameter from which to base design calculations on due to the brittle behavior of multiple-bolt connections. Typically, connections with five bolts per row failed suddenly with little or no non-linear response so that the 5% offset yield strength was determined to be close to connection capacity. This was the typical for all multiple-bolt connections with the exception of the three bolts per row configurations of the ST and 46 series, which is perhaps why there is a noticeable reduction in 5% offset yield strength per bolt between single-bolt and three-bolt configurations.

Overall the comparison of the 5% offset yield strength between ductile (Figure 4.45A) and brittle connections (Figure 4.45B&C), single-bolt and multiple-bolt, is inconsistent because the parameter itself is dependent upon other variable parameters and limited by the connection capacity. The initial stiffness, based on the envelope curve, was typically dependent upon the alignment of the bolt-holes at the start of the test which, introduces the possibility of unequal load distribution among bolts in a row and multiple values of stiffness in what appeared to be the linear portion of the load-deflection plot. The 5% offset yield strength accuracy is further complicated by multiple-bolt connections in which there was not sufficient non-linear response before failure to offset a line 5% of the bolt diameter, parallel to the elastic portion of the load-deflection plot with out passing the line beyond the connection capacity; at which point 5% offset yield strength was defined as being equal to the connection capacity (Figure 4.45C).

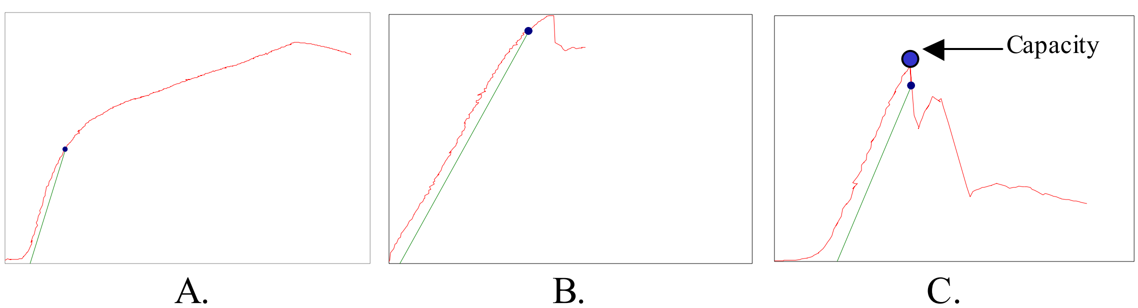

Figure 4.45: Examples of 5% offset yield strength determination.

4.6.4 - Capacity

To observe the trends in each of the connection configurations, connection capacity data has been divided by the total number of bolts, based on the specific connection configuration, and normalized so that the mean normalized connection capacity for single-bolt configurations is equal to 1.00. This approach is used to determine the group action factor, C_g, as it is shown in Equation 2.1. The capacity data and group action factor data can be found in Tables 4.35, 4.37, 4.40, and 4.42 for each respective test series. Plots concerning the group action factor based on connection capacity are shown in Figures 4.46, 4.47, 4.48, and 4.49. To make inferences about the relationship between different bolt configurations within each test series it is assumed that data is normally distributed about the mean and population variances are equal. Two-sample t-tests are used to test the null hypothesis that any two population means are equal, using a level of significance, α, equal to 0.05. Decisions concerning the difference between two means, and t-statistics, can be found in Tables 4.36, 4.38, 4.40, and 4.42.

Table 4.35: Test and GAF data at capacity, 2X Series.

Test Capacity (lbs.)

Specimen	2X1R1C	2X1R3C	2X1R5C	2X2R3C	2X2R5C
Spec 1	2737.85	5412.84	8310.61	11172.30	20929.54
Spec 2	2221.32	5310.58	8387.31	11617.41	13741.50
Spec 3	4165.53	6024.12	7521.13	10121.16	16350.55
Spec 4	2268.61	6255.70	7963.24	11794.86	15276.85
Spec 5	2515.43	7230.15	9572.28	13583.60	18064.10
Spec 6	2705.34	5491.79	9527.17	12698.63	18347.56
Spec 7	2708.29	5793.29	8315.12	12182.83	15393.39
Spec 8	3292.81	5783.52	9134.68	14320.45	16884.39
Spec 9	2699.43	6623.38	10209.13	11708.39	17751.31
Spec 10	2381.67	5932.39	7830.91	9723.41	13279.84
Mean	2769.63	5985.78	8677.16	11892.30	16601.90

Group Action Factor Data

Specimen	2X1R1C	2X1R3C	2X1R5C	2X2R3C	2X2R5C
Spec 1	0.99	0.65	0.60	0.67	0.76
Spec 2	0.80	0.64	0.61	0.70	0.50
Spec 3	1.50	0.73	0.54	0.61	0.59
Spec 4	0.82	0.75	0.58	0.71	0.55
Spec 5	0.91	0.87	0.69	0.82	0.65
Spec 6	0.98	0.66	0.69	0.76	0.66
Spec 7	0.98	0.70	0.60	0.73	0.56
Spec 8	1.19	0.70	0.66	0.86	0.61
Spec 9	0.97	0.80	0.74	0.70	0.64
Spec 10	0.86	0.71	0.57	0.59	0.48
Mean	1.00	0.72	0.63	0.72	0.60
StDev	0.21	0.07	0.06	0.09	0.08

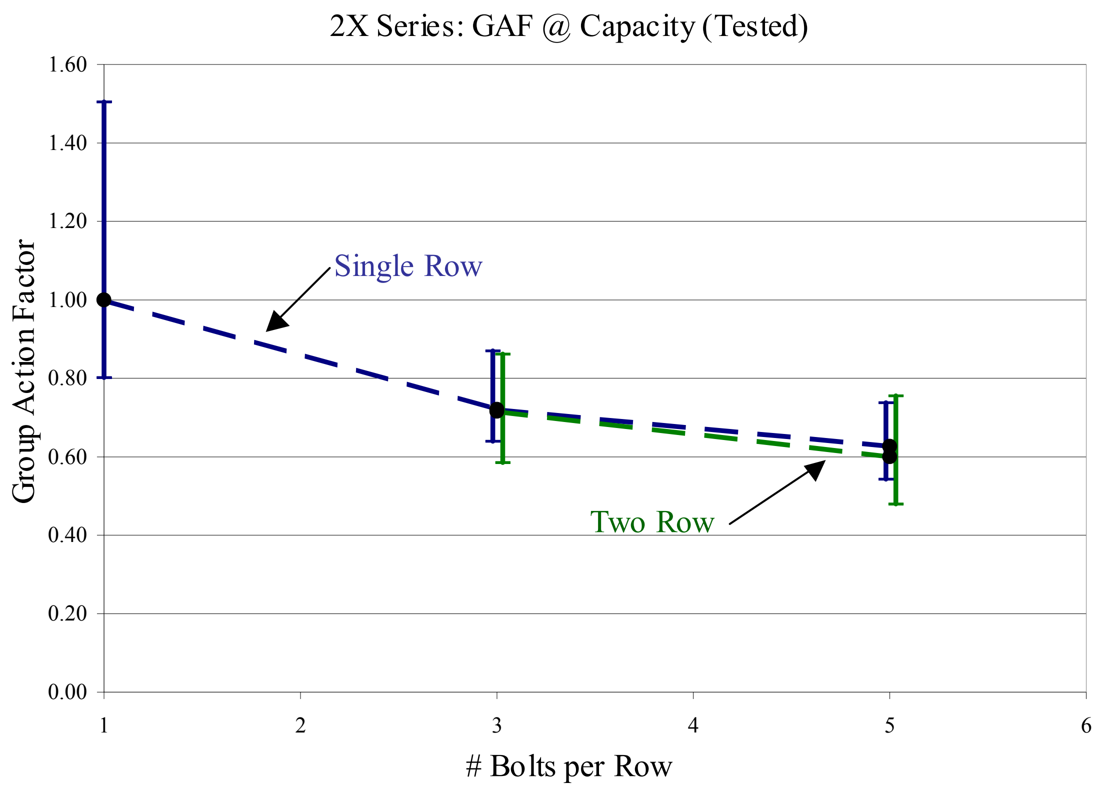

Figure 4.46: Group Action Factor based on capacity, 2X Series.

Table 4.36: Inferences concerning means, 2X Series.

t-statistic for small sample test concerning difference between two means.

	2X1R1C	2X1R3C	2X1R5C	2X2R3C	2X2R5C
2X1R1C	0				
2X1R3C	4.01	0			
2X1R5C	5.42	3.11	0		
2X2R3C	3.99	0.14	-2.65	0	
2X2R5C	5.64	3.50	0.82	3.09	0

$t_{\alpha/2}$ = 2.11 (Level α = 0.05 and 18 dof's)

Decision concerning difference between two means

	2X1R1C	2X1R3C	2X1R5C	2X2R3C	2X2R5C
2X1R1C	0				
2X1R3C	Reject H_o	0			
2X1R5C	Reject H_o	Reject H_o	0		
2X2R3C	Reject H_o	C.R. H_o	Reject H_o	0	
2X2R5C	Reject H_o	Reject H_o	C.R. H_o	Reject H_o	0

Reject H_o: Reject null hypothesis that means are equal.

C.R. H_o: Cannot reject null hypothesis that means are equal

Table 4.37: Test and GAF data at capacity, ST Series.

Test Capacity (lbs.)

Specimen	ST1R1C	ST1R3C	ST1R5C	ST2R3C	ST2R5C
Spec 1	3133.12	6291.04	12482.84	12993.37	18768.62
Spec 2	2907.55	7066.99	9522.66	14004.66	20401.72
Spec 3	2920.33	6751.20	10177.55	14983.61	21306.24
Spec 4	3277.48	5607.58	8887.31	13248.26	18500.19
Spec 5	3327.10	5415.09	10038.45	13472.32	21349.85
Spec 6	2778.98	6715.11	9015.88	11526.44	20329.53
Spec 7	2945.14	6352.70	7044.43	11200.12	18886.66
Spec 8	3218.83	6894.06	12149.75	11350.49	16286.64
Spec 9	2668.45	5736.15	9942.96	13224.20	20046.83
Spec 10	3140.63	6785.03	10236.20	14371.58	19724.26
Mean	3031.76	6361.49	9949.80	13037.50	19560.05

Group Action Factor Data

Specimen	ST1R1C	ST1R3C	ST1R5C	ST2R3C	ST2R5C
Spec 1	1.03	0.69	0.82	0.71	0.62
Spec 2	0.96	0.78	0.63	0.77	0.67
Spec 3	0.96	0.74	0.67	0.82	0.70
Spec 4	1.08	0.62	0.59	0.73	0.61
Spec 5	1.10	0.60	0.66	0.74	0.70
Spec 6	0.92	0.74	0.59	0.63	0.67
Spec 7	0.97	0.70	0.46	0.62	0.62
Spec 8	1.06	0.76	0.80	0.62	0.54
Spec 9	0.88	0.63	0.66	0.73	0.66
Spec 10	1.04	0.75	0.68	0.79	0.65
Mean	1.00	0.70	0.66	0.72	0.65
StDev	0.07	0.06	0.10	0.07	0.05

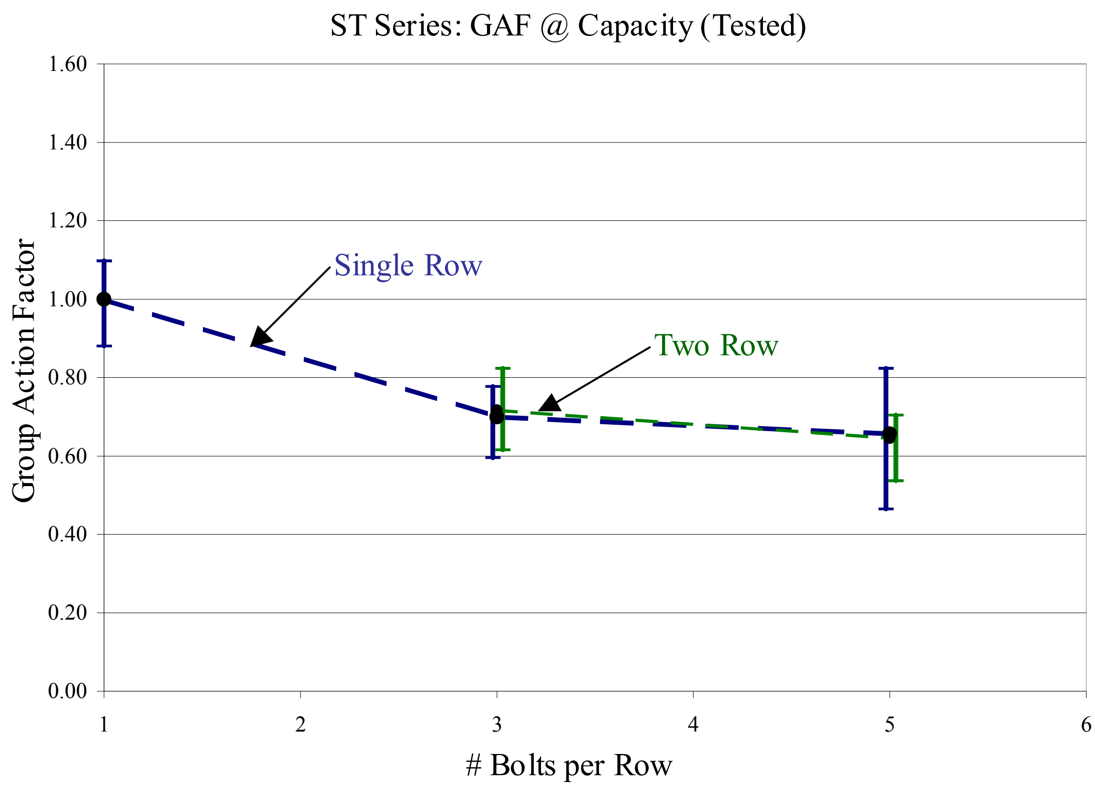

Figure 4.47: Group Action Factor based on capacity, ST Series.

Table 4.38: Inferences concerning means, ST Series.

t-statistic for small sample test concerning difference between two means.

	ST1R1C	ST1R3C	ST1R5C	ST2R3C	ST2R5C
ST1R1C	0				
ST1R3C	9.79	0			
ST1R5C	8.61	1.12	0		
ST2R3C	8.78	-0.57	-1.52	0	
ST2R5C	12.72	2.10	0.31	2.59	0

$t_{\alpha/2}$ = 2.11 (Level α = 0.05 and 18 dof's)

Decision concerning difference between two means

	ST1R1C	ST1R3C	ST1R5C	ST2R3C	ST2R5C
ST1R1C	0				
ST1R3C	Reject H_o	0			
ST1R5C	Reject H_o	C.R. H_o	0		
ST2R3C	Reject H_o	C.R. H_o	C.R. H_o	0	
ST2R5C	Reject H_o	C.R. H_o	C.R. H_o	Reject H_o	0

Reject H_o: Reject null hypothesis that means are equal.

C.R. H_o: Cannot reject null hypothesis that means are equal

Table 4.39: Test and GAF data at capacity, 46 Series.

Test Capacity (lbs.)

Specimen	461R1C	461R3C	461R5C	462R3C	462R5C
Spec 1	2914.32	5044.41	8489.56	9287.31	13905.41
Spec 2	2494.01	4818.85	8551.97	9946.72	17121.23
Spec 3	3093.27	5471.49	8168.51	10648.23	17209.20
Spec 4	3178.23	4497.04	7409.85	10353.49	16820.48
Spec 5	2724.84	4367.71	8476.03	11998.62	15936.26
Spec 6	2381.98	5185.77	9021.90	9182.05	14418.95
Spec 7	2996.27	5811.34	7978.28	9920.40	16083.63
Spec 8	2136.11	5128.62	7585.04	9739.95	14018.94
Spec 9	2140.62	4562.45	8322.64	10573.79	14978.35
Spec 10	2978.98	4547.42	7724.14	11215.15	12967.80
Mean	2703.86	4943.51	8172.79	10286.57	15346.02

Group Action Factor Data

Specimen	461R1C	461R3C	461R5C	462R3C	462R5C
Spec 1	1.08	0.62	0.63	0.57	0.51
Spec 2	0.92	0.59	0.63	0.61	0.63
Spec 3	1.14	0.67	0.60	0.66	0.64
Spec 4	1.18	0.55	0.55	0.64	0.62
Spec 5	1.01	0.54	0.63	0.74	0.59
Spec 6	0.88	0.64	0.67	0.57	0.53
Spec 7	1.11	0.72	0.59	0.61	0.59
Spec 8	0.79	0.63	0.56	0.60	0.52
Spec 9	0.79	0.56	0.62	0.65	0.55
Spec 10	1.10	0.56	0.57	0.69	0.48
Mean	1.00	0.61	0.60	0.63	0.57
StDev	0.14	0.06	0.04	0.05	0.06

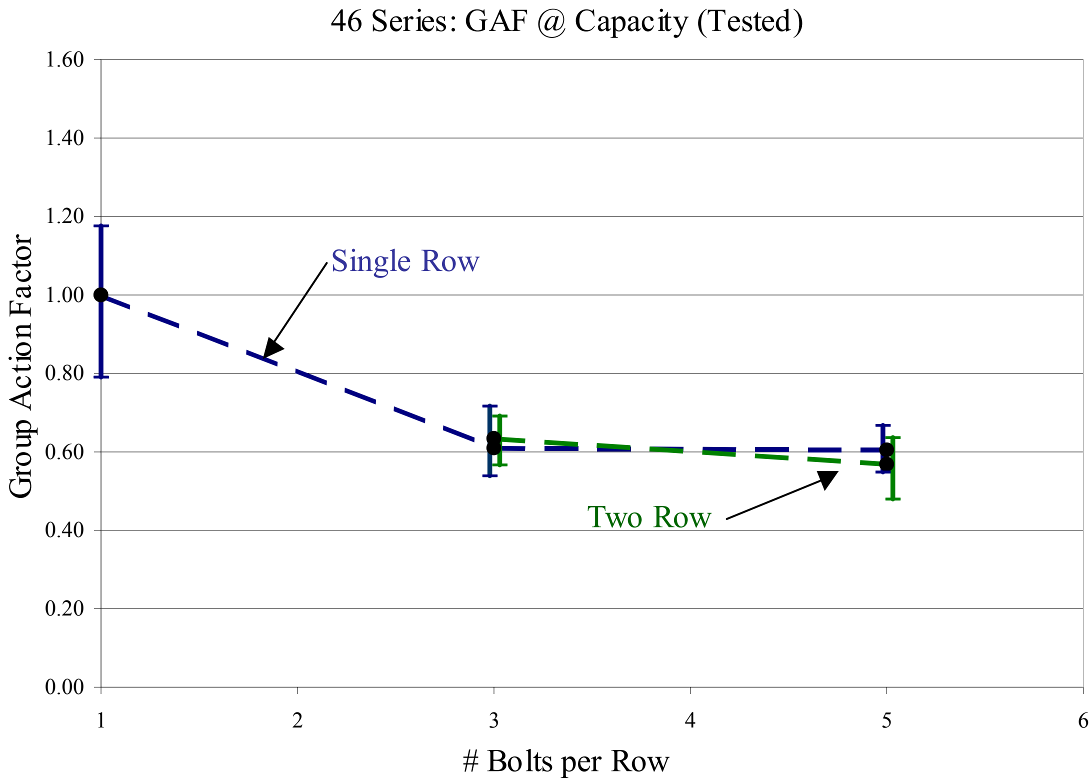

Figure 4.48: Group Action Factor based on capacity, 46 Series.

Table 4.40: Inferences concerning means, 46 Series.

t-statistic for small sample test concerning difference between two means.

	461R1C	461R3C	461R5C	462R3C	462R5C
461R1C	0				
461R3C	7.94	0			
461R5C	8.40	0.23	0		
462R3C	7.52	-0.99	-1.44	0	
462R5C	8.85	1.65	1.76	2.73	0
$t_{\alpha/2}$ =	2.11	(Level α = 0.05 and 18 dof's)			

Decision concerning difference between two means

	461R1C	461R3C	461R5C	462R3C	462R5C
461R1C	0				
461R3C	Reject H_o	0			
461R5C	Reject H_o	C.R. H_o	0		
462R3C	Reject H_o	C.R. H_o	C.R. H_o	0	
462R5C	Reject H_o	C.R. H_o	C.R. H_o	Reject H_o	0

Reject H_o: Reject null hypothesis that means are equal.

C.R. H_o: Cannot reject null hypothesis that means are equal

Table 4.41: Test and GAF data at capacity, 4X Series.

Test Capacity (lbs.)

Specimen	4X1R1C	4X1R3C	4X1R5C
Spec 1	2750.40	6021.87	10248.98
Spec 2	3290.26	4899.30	10346.72
Spec 3	3426.35	6391.80	7686.55
Spec 4	4066.96	6602.32	9909.88
Spec 5		6233.15	10473.79
Spec 6	3093.27	8793.32	11213.65
Spec 7	4206.81	5758.71	13093.37
Spec 8	3191.76	7059.47	9558.75
Spec 9	3088.00	7191.80	8182.79
Spec 10	3528.61		9233.18
Mean	3404.71	6550.19	9994.77

Group Action Factor Data

Specimen	4X1R1C	4X1R3C	4X1R5C
Spec 1	0.81	0.59	0.60
Spec 2	0.97	0.48	0.61
Spec 3	1.01	0.63	0.45
Spec 4	1.19	0.65	0.58
Spec 5		0.61	0.62
Spec 6	0.91	0.86	0.66
Spec 7	1.24	0.56	0.77
Spec 8	0.94	0.69	0.56
Spec 9	0.91	0.70	0.48
Spec 10	1.04		0.54
Mean	1.00	0.64	0.59
StDev	0.14	0.11	0.09

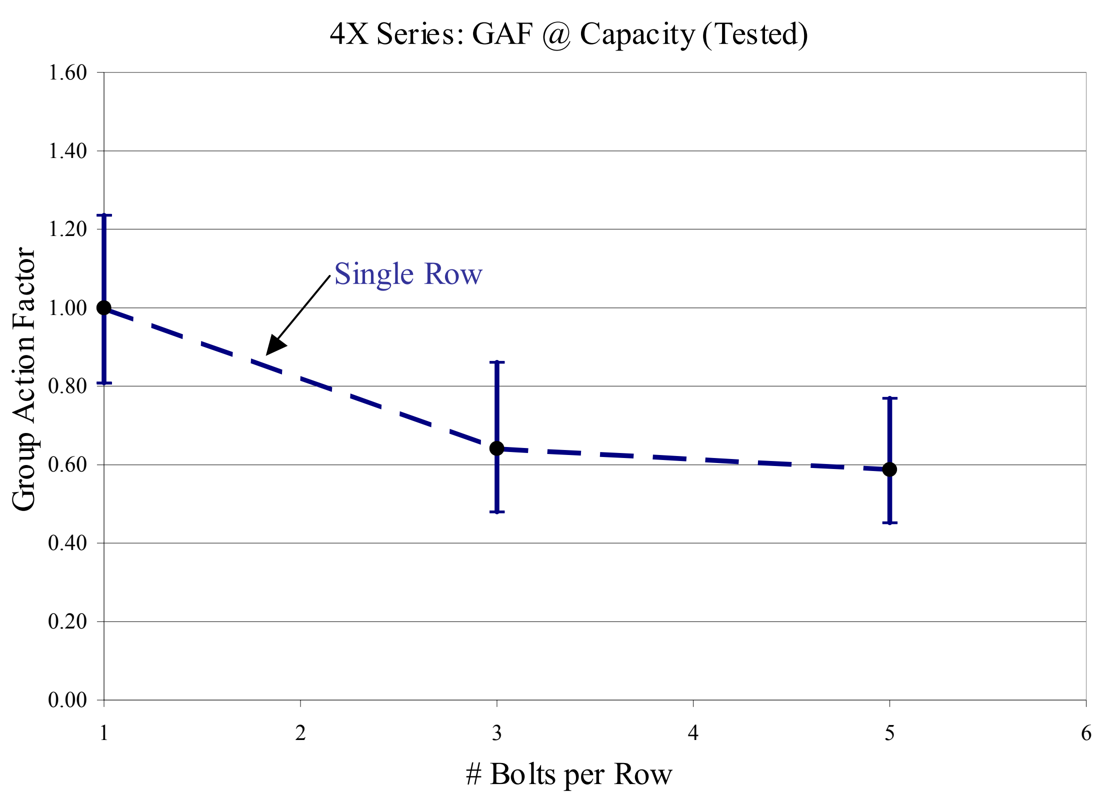

Figure 4.49: Group Action Factor based on capacity, 4X Series.

Table 4.42: Inferences concerning means, 4X Series.

t-statistic for small sample test concerning difference between two means.

	4X1R1C	4X1R3C	4X1R5C
4X1R1C	0		
4X1R3C	6.16	0	
4X1R5C	7.80	1.20	0
$t_{\alpha/2}$ =	2.11	(Level α = 0.05 and 18 dof's)	

Decision concerning difference between two means

	4X1R1C	4X1R3C	4X1R5C
4X1R1C	0		
4X1R3C	Reject H_o	0	
4X1R5C	Reject H_o	C.R. H_o	0

Reject H_o: Reject null hypothesis that means are equal.

C.R. H_o: Cannot reject null hypothesis that means are equal

Inferences concerning means indicate that, within each test series, a significant statistical difference exists between single-bolt and multiple-bolt connections when based on the group action factor at capacity. Concerning the difference between multiple bolt connections in general, results indicate that within the 2X series significant statistical difference concerning means exists between connections with three bolts per row and five bolts per row. Within the 46 series and ST series, the only statistical difference in means was noted between three-bolt two-row and five-bolt two-row connections. The greatest relative drop in maximum load per fastener was determined to be when the number of bolts per row was increased from one to three. On the other hand, an increase from three to five bolts per row typically produced only slight statistical difference in group action. This indicates that if the bolt spacing requirements remain at 4D, then the group action factor based on capacity could be changed to a single value for all multiple-bolt connections.

Results also indicate that for a constant number of bolts per row the observed difference between single and two-row means is not significant. Consequently it cannot be proved that there is no row interaction concerning connection capacity, but it also cannot be disproved at a level of significance, α, equal to 0.05. The row spacing for all multiple-row connections tested was 2 in. setting the lower limit for this observation at 4D, or four times the bolt diameter, based on the use of 1/2 in. diameter bolts in the 2X series. It cannot be determined from this investigation whether the NDS minimum requirement for row spacing, 1.5D, would produce the same conclusion.

This research does not provide results for connections with two or four bolts per row, nor more than five bolts per row. However, Heine (2001) developed a general numeric model that is capable of predicting the load-displacement relationship up to and including failure of multiple-bolt timber joints of various configurations. The model is not tied to a single input function and bolt-holes are permitted to be oversized resulting in a slack system. Results from a parametric study of group action in cyclically loaded bolted connections as determined by Heine (2001) are shown in Figure 4.50. Results of joints containing 1, 2, 4, 6, 8, 10 bolts spaced 4D and 7D are shown as well as test results, for connections utilizing 1.5 in. x 5.5 in. southern yellow pine main and side members with 1/2 in. diameter bolts.

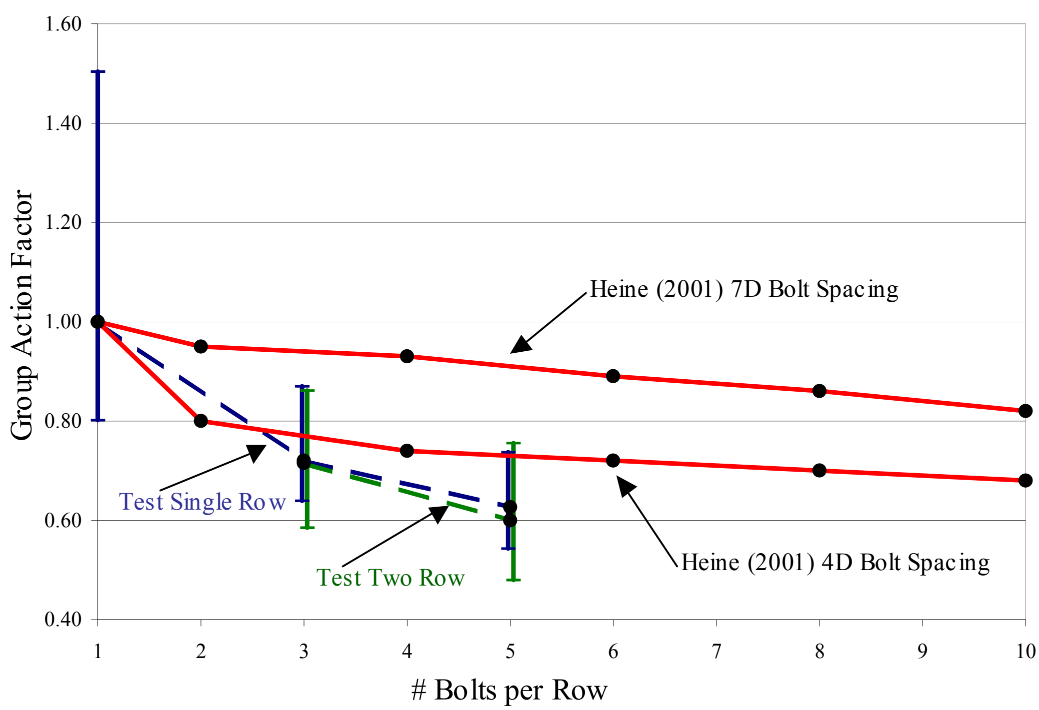

Figure 4.50: Group action factor at capacity for joints displaced cyclically based on test results and model results from Heine (2001) (bolt diameter D = 1/2 in., southern pine members 1.5 in. x 5.5 in.).

For this experimental study spacing between bolts in a row was 4D, or four times the bolt diameter, per the 1997 NDS recommendations for bolted connection design. It is felt that the issue of brittle connection failure illustrated by normalized ductility ratios, the group action factor based on capacity, and the observations of mixed mode yield are due to inadequate bolt spacing. In light of these trends it is apparent that substantial redistribution of load among bolts in a row did not take place due to the typically brittle manner in which failure occurred. This statement is compounded by the fact that typically, single-bolt connections with an end distance of 7D performed much better and had significant inelastic response in comparison to multiple-bolt connections, indicating the validity of a 7D end distance requirement. A parallel study that modeled multiple-bolt connections by Heine (2001) also indicated that a minimum spacing of 4D was inadequate and should be increased to 7D for improved performance (Figure 4.50).

4.7 – Yield Limit Model Predictions

The design of multiple bolt connections is a function of the number of bolts, the group action factor, and single-bolt strength values. Current design practice is based on the 1997 NDS, and utilizes a group action factor based on load distribution at proportional limit and the design value based on 5% offset yield strength of a single-bolt connection using the YLM model. Use of a group action factor is only valid if the prediction of single-bolt strength is accurate, and vice versa. This chapter has already presented findings related to the group action factor at the 5% offset yield strength and at capacity so the emphasis of this section is on the ability of the Yield Limit Model to predict single-bolt strengths at these levels.

To observe the trends in each of the connection configurations, capacity and 5% offset yield strength for both the YLM prediction and single-bolt test results are compared. Predicted and tested strength data can be found in Tables 4.43, 4.45, 4.47, and 4.49 for each respective test series. Plots concerning tested and predicted strengths are shown in Figures 4.51, 4.52, 4.53, and 4.54 where mean single bolt strength values are shown with range bars indicating the maximum and minimum values as an indication of the distribution of data around the mean. To make inferences about the appropriateness of model predictions as compared to tested strengths it is assumed that data is normally distributed about the mean and population variances are equal. Two-sample t-tests are used to test the null hypothesis that any two population means are equal, using a level of significance, α, equal to 0.05. Decisions concerning the difference between two means, and t-statistics, can be found in Tables 4.44, 4.46, 4.48, and 4.50.

Material properties utilized in the YLM came from fastener bending test results, Table 4.51, and dowel embedment test results, which can be found in Appendix B. Information in Table 4.51 also shows the recommended bolt bending stresses per Technical Report 12 (AFPA, 1999), which are substantially lower than test results.

Table 4.43: Test and YLM data at capacity and 5% offset yield strength, 2X Series.

	Tested		YLM Prediction	
	Capacity	5% Offset	Capacity	5% Offset
Spec 1	2737.85	1718.17	1663.76	1646.72
Spec 2	2221.32	1390.46	1480.20	1446.09
Spec 3	4165.53	2092.54	2029.18	2006.26
Spec 4	2268.61	1547.70	1579.27	1575.75
Spec 5	2515.43	1305.11	1372.03	1342.62
Spec 6	2705.34	1498.74	1428.43	1412.25
Spec 7	2708.29	1442.00	1302.43	1275.15
Spec 8	3292.81	1711.31	1824.62	1789.08
Spec 9	2699.43	1859.22	2020.68	1917.47
Spec 10	2381.67	1473.78	1550.04	1540.86
Mean	2769.63	1603.90	1625.06	1595.23

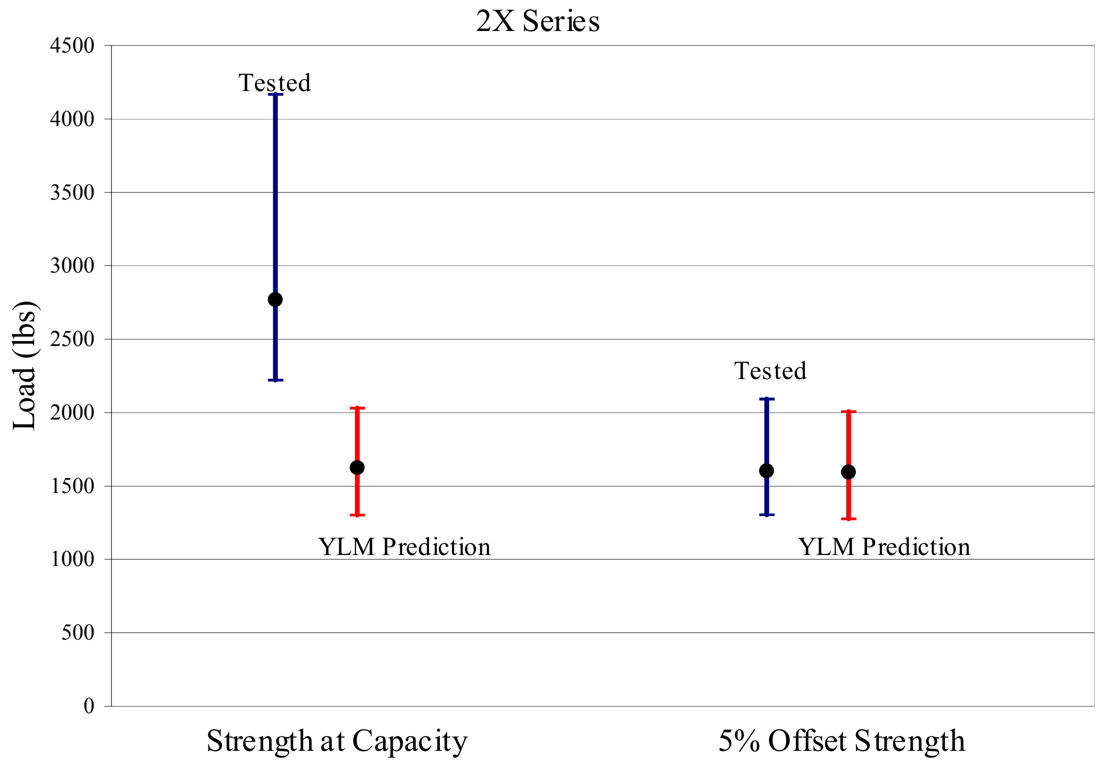

Figure 4.51: Comparison of YLM predicted loads and test loads, 2X Series.

Table 4.44: Inferences concerning means, 2X Series.

	Capacity	5% offset yield strength
t-stat	5.72	0.08
Decision	Reject H_o	C.R. H_o

$t_{\alpha/2}$ = 2.10 (Level α = 0.05 and 18 dof's)

Reject H_o: Reject null hypothesis that means are equal.

C.R. H_o: Cannot reject null hypothesis that means are equal

Table 4.45: Test and YLM data at capacity and 5% offset yield strength, ST Series.

	Tested		YLM Mode III		YLM Mode IV	
	Capacity	5% Offset	Capacity	5% Offset	Capacity	5% Offset
Spec 1	3133.12	2187.57	1865.90	1479.54	2215.60	1809.80
Spec 2	2907.55	1843.60	1739.24	1376.51	2052.93	1672.69
Spec 3	2920.33	1727.11	1981.57	1573.92	2365.70	1936.77
Spec 4	3277.48	2069.68	1958.15	1519.32	2335.20	1863.15
Spec 5	3327.10	1898.11	1827.51	1445.36	2166.11	1764.14
Spec 6	2778.98	2330.10	1919.70	1519.22	2285.24	1863.02
Spec 7	2945.14	2305.67	1981.34	1555.50	2365.40	1911.89
Spec 8	3218.83	1999.31	2060.90	1654.30	2469.48	2045.94
Spec 9	2668.45	1831.22	1775.08	1427.31	2098.78	1740.10
Spec 10	3140.63	1590.16	2022.50	1527.48	2419.16	1874.13
Mean	3031.76	1978.25	1913.19	1507.85	2277.36	1848.16

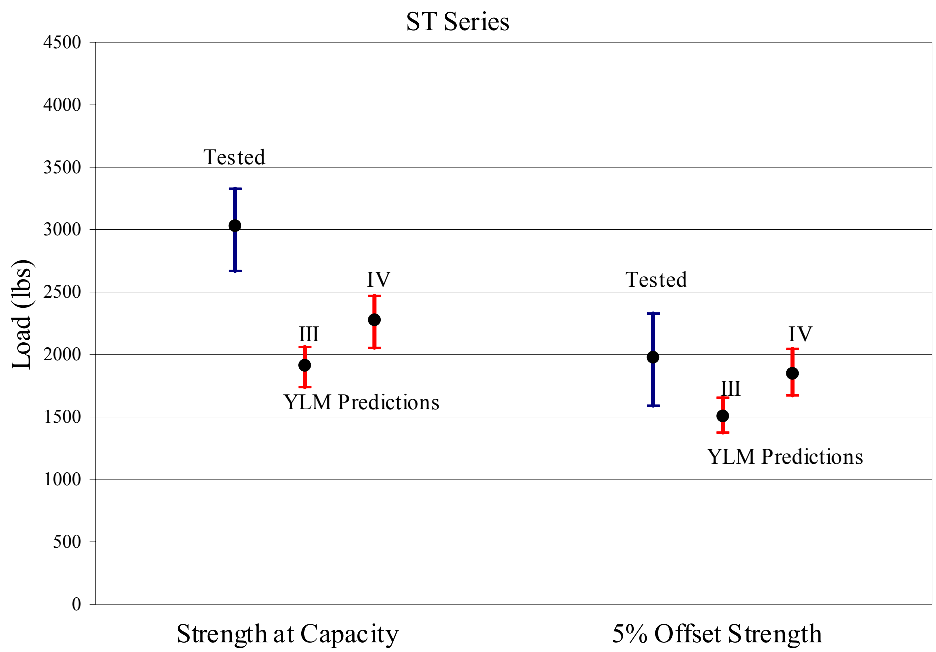

Figure 4.52: Comparison of YLM predicted loads and test loads, ST Series.

Table 4.46: Inferences concerning means, ST Series.

	Tested vs. YLM (Mode III)		Tested vs. YLM (Mode IV)	
	Capacity	5% offset yield strength	Capacity	5% offset yield strength
t-stat	14.44	5.76	9.16	1.53
Decision	Reject H_o	Reject H_o	Reject H_o	C.R. H_o

$t_{\alpha/2}$ = 2.1 (Level α = 0.05 and 18 dof's)

Reject H_o: Reject null hypothesis that means are equal.

C.R. H_o: Cannot reject null hypothesis that means are equal

Table 4.47: Test and YLM data at capacity and 5% offset yield strength, 46 Series.

	Tested		YLM Prediction	
	Capacity	5% Offset	Capacity	5% Offset
Spec 1	2914.32	1286.87	1714.45	1537.12
Spec 2	2494.01	1512.84	1636.76	1438.73
Spec 3	3093.27	1533.52	1729.37	1554.07
Spec 4	3178.23	1498.75	1777.60	1566.85
Spec 5	2724.84	1390.68	1733.68	1551.27
Spec 6	2381.98	1260.37	1687.47	1462.86
Spec 7	2996.27	1489.40	2068.68	1829.73
Spec 8	2136.11	1432.35	1726.01	1554.11
Spec 9	2140.62	1178.92	1602.10	1418.88
Spec 10	2978.98	1594.99	1776.31	1569.78
Mean	2703.86	1417.87	1745.24	1548.34

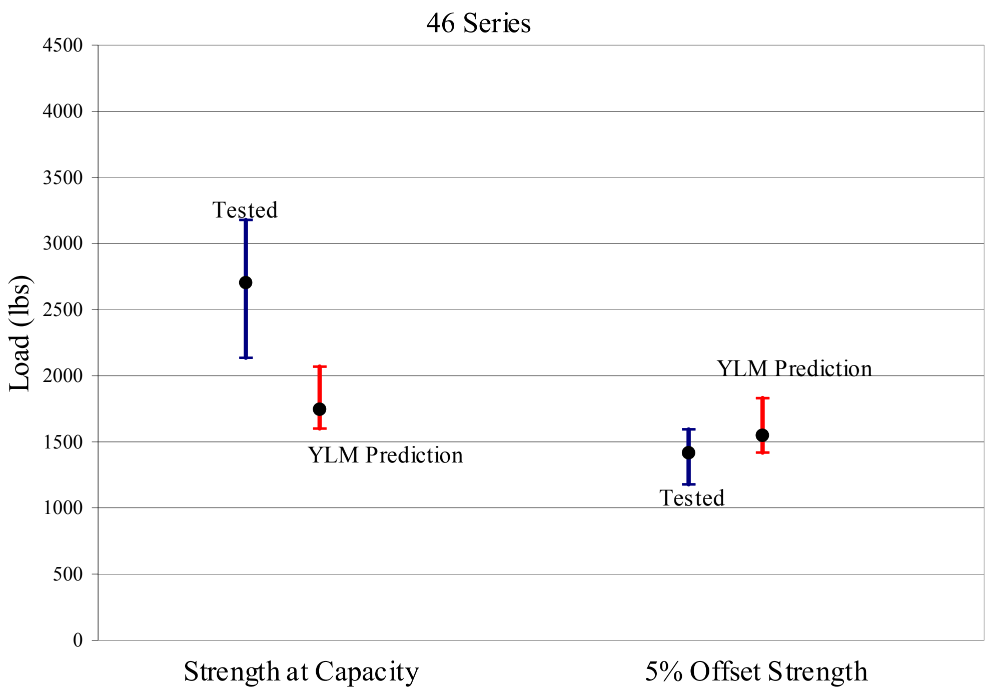

Figure 4.53: Comparison of YLM predicted loads and test loads, 46 Series.

Table 4.48: Inferences concerning means, 46 Series.

	Capacity	5% offset yield strength
t-stat	7.39	-2.33
Decision	Reject H_o	Reject H_o

$t_{\alpha/2}$ = 2.1 (Level α = 0.05 and 18 dof's)

Reject H_o: Reject null hypothesis that means are equal.

Table 4.49: Test and YLM data at capacity and 5% offset yield strength, 4X Series.

	Tested		YLM Prediction	
	Capacity	5% Offset	Capacity	5% Offset
Spec 1	2750.40	1571.26	2767.60	2569.57
Spec 2	3290.26	1725.13	2926.26	2725.55
Spec 3	3426.35	2536.90	2847.71	2592.34
Spec 4	4066.96	2038.33	3154.59	2883.77
Spec 5				
Spec 6	3093.27	2408.48	2780.39	2495.82
Spec 7	4206.81	2264.13	3406.62	3141.12
Spec 8	3191.76	1582.32	2794.60	2590.02
Spec 9	3088.00	1567.82	2766.51	2572.44
Spec 10	3528.61	2017.77	2887.22	2684.66
Mean	3404.71	1968.02	2925.72	2695.03

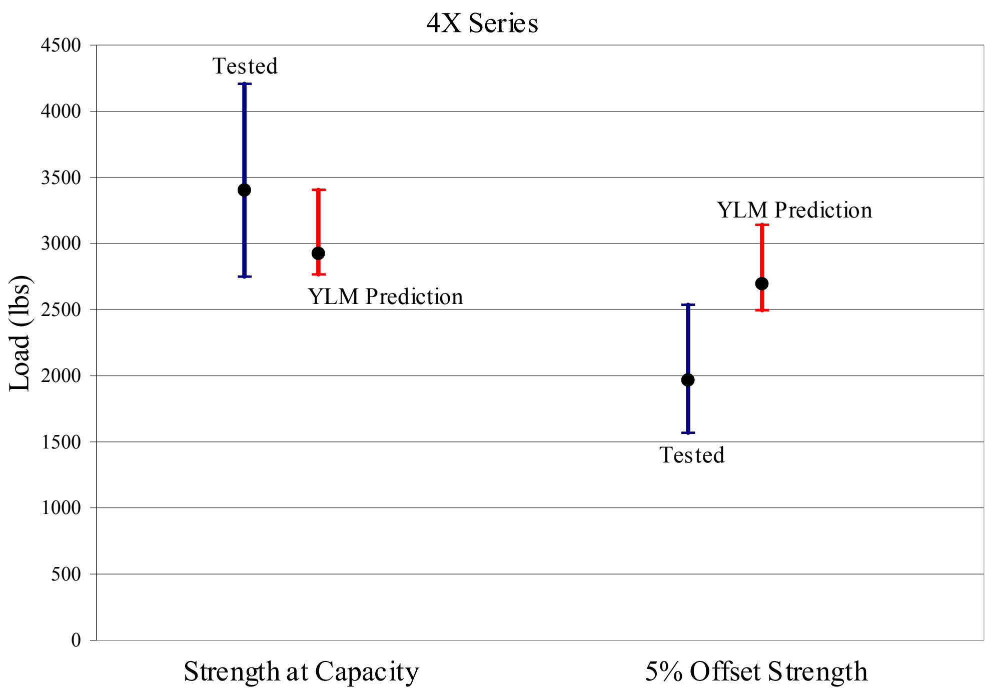

Figure 4.54: Comparison of YLM predicted loads and test loads, 4X Series.

Table 4.50: Inferences concerning means, 4X Series.

	Capacity	5% offset yield strength
t-stat	2.76	-5.10
Decision	Reject H_o	Reject H_o

$t_{\alpha/2} =$ 2.12 (Level α = 0.05 and 16 dof's)

Reject H_o: Reject null hypothesis that means are equal.

Table 4.51: Recommended and tested bolt bending stresses.

Series	Bolt Diameter	5% Offset Yield psi (cov %)	Ultimate Strength psi (cov %)
All	Recommended*	45000	60000
ST	3/8"	60852.12 (8.0)	82437.61 (8.0)
46	3/8"	78218.45 (9.0)	91003.34 (9.0)
4X	1/2"	77691.41 (5.0)	88411.30 (5.0)

* Based on recommendations in Technical Report 12 (AFPA, 1999)

Inferences concerning means indicate that there is a significant statistical difference between tested connection capacity and the YLM connection capacity prediction. For the connection configurations included in this study the YLM underestimates the tested single-bolt connection capacity in all cases.

Results pertaining to the 5% offset yield strength indicate that there is no statistical difference between test values and YLM predictions for single-bolt connections in the 2X and ST series. However, there is a significant statistical difference for single-bolt connections in the 46 and 4X series. The YLM over predicts the 5% offset yield strength in these cases.

Material sampling, material property testing, and assumptions inherent to the Yield Limit Model directly affect trends noted in both the 5% offset yield strength and capacity predictions when compared to tested values. It is possible that a combination of these topics produced the deviations in predicted strength versus tested strength.

Material samples were taken from connection members after testing and could not be taken along the line of action of the load because of cracks and other miscellaneous damage. The material in the line of action of the bolt row may have been different from the material at the sample location because of where samples were taken as shown in Figure 3.9. Lumber used in the 2X series of connection tests was typically uniform in growth ring patterns across the cross-section with little indication of juvenile wood. This resulted in dowel embedment samples that were similar to the material surrounding a bolt-hole. Timber members used in all other tests were typically “boxed heart” such that bolt bearing was on juvenile wood while the dowel embedment samples were performed on the material in transition between juvenile and mature wood. It is possible that the difference in strength properties between connection and sample locations caused the deviations in predicted 5% offset yield strength compared to the test results for the 46 and 4X series.

Underestimation of connection capacity by the YLM may be due to the dowel embedment test method and the assumptions inherent to the model. The dowel embedment test was conducted in the full-hole configuration so that premature splitting of the specimen did not produce an underestimation of capacity. An inherent problem with full-hole testing is that the test dowel elastically deflects from the resisting load provided by the wood specimen and thus non-uniform stress distribution is introduced. The testing fixture was designed to limit this problem but it cannot be totally prevented. Non-uniform stress distribution may have caused an underestimation of the stress at capacity in dowel embedment specimens.

The Yield Limit Model does not account for end fixity or friction between the members caused by tensioning of the bolt. In the case of connections constructed with steel side plates, ST series, it is apparent that the washers prevented the rotation of the dowel ends and thus introduced an alternative load distribution through the thickness of the member in which, two plastic hinges formed in the bolt. End fixity also allowed for tensioning of the bolt at significant displacements such that substantial friction developed at the member interfaces, or shear plane, and a component of the tension force acts to resist the applied load. Because the 5% offset yield strength occurs so early in the inelastic response it is possible that end fixity and friction are not substantial enough to introduce significant error in the model prediction values. At capacity however, end fixity provided by the washers creates significant friction as evidenced by the crushing of wood underneath washers and the occasional necking of the bolt at hinge locations. At capacity, the assumption of a frictionless joint may not be valid causing an underestimation of the capacity strength by the YLM. Furthermore, by not taking into account end fixity, the YLM may not predict the correct yield mode.