Chapter 4 – Results and Discussion

4.1 – General

The objectives of this research are: 1) develop physical data on the behavior and mechanics of nailed and bolted single-shear laterally-loaded connections up to and beyond capacity, and 2) using this data, quantify the safety factors and over-strengths of design values currently stipulated by the NDS and LRFD *Manual for Engineered Wood Construction* on a capacity basis.

Six-hundred-eighty-one single-shear, single-fastener connection specimens were fabricated using materials common in wood construction and tested monotonically in tension. For nailed connections, test variables included side member material type, side member thickness, and nail length and diameter. Bolted connection test variables included commercial lumber species group, main member thickness, and bolt length and diameter. Two embedment tests were conducted for each connection test, one corresponding to the main member and one corresponding to the side member. Data from these tests were used to quantify each member's bearing strength. Additionally, ten fastener bending tests were conducted for each fastener type in order to quantify the average bending yield strength of each.

All of the aforementioned tests were conducted under displacement-controlled loading conditions with the actuator moving at a specified constant rate. For each of these tests, displacements and corresponding loads (resistances) were recorded with an automated data acquisition system, as described in Chapter 3. One "raw" data file was generated in ASCII format for each test. These raw data files were then grouped by set into a spreadsheet and analyzed with a program written specifically for analysis of monotonic load-deflection data. Program output is presented in tabulated form for each connection specimen in Appendix B. Average results as well as their associated coefficients of variation (COVs) are presented throughout this chapter in the form of representative values including the following:

- resistance, displacement, and energy input up to: 1) 5% offset yield, 2) equivalent elastic-plastic energy yield, 3) first local maximum, 4) capacity, and 5) failure,

- elastic stiffness, and
- ductility ratio.

Average load-deflection plots on a set-wise basis are also presented. Due to the fact that the individual connections within a set often reached capacity at varying deflections, the apparent capacity of said set's average load-deflection curve will always be *equal* to or *less* than the set's actual average capacity. This is true of other arbitrary points along the load-deflection curve as well. It must also be noted that the average load-deflection curve of a set is plotted only within the domain of deflections for which all individual load-deflection functions within the set had values. Thus, if one connection test within a given set was aborted relatively early due to premature connection failure, the average load-deflection plot would extend only to the deflection associated with the earliest specimen failure. The reader is referred to Appendix A for load-deflection plots of each *individual* connection test.

Connection tests were run either until failure, or until the testing machine crosshead reached the limit of its mobile range. Because of this and the fact that tests were conducted by displacement control rather than load control (i.e., capacity did not necessarily represent the point of incipient failure), many connections did not reach failure, as defined in Section 3.7, even after capacity was reached. This was especially true of the more ductile specimens.

Theoretical connection resistance values were calculated using the yield model and compared to experimentally derived connection resistances at both 5% offset yield and capacity. Input parameters for these calculations included embedment (bearing) resistance obtained from the results of embedment tests for both main and side members, the plastic moment of the fastener obtained from bending tests, and bearing lengths of the fastener within both the main and side members. Results of statistical comparisons between experimental values and calculated values are presented in this chapter as well.

4.2 – Nailed Connection Tests

A total of four-hundred-eighty-two nailed connections were tested. With the exception of two sets (those which had solid wood side members), all of these were fabricated such that they simulated typical connections found between sheathing and framing members in light-frame wood construction. Main member materials were either SPF or Southern Pine nominal 2x4, and side member materials consisted of either gypsum wallboard, structural fiberboard, hardboard siding, OSB, plywood, or solid wood nominal 2x4 sections. Side member thickness varied between 0.40" and 1.50" depending upon its respective material type and the mill at which it was manufactured. Consequently, penetration of the nail into the main member, which is a function of nail length and side member thickness, varied as well. Nail types varied in length and diameter from the smallest (drywall nail) which had dimensions of 1 $^3/_8$" in length and 0.099" diameter to the largest (16d common nail) – having a length of 3 ½" and a diameter of 0.162". All nails were smooth-shanked and all were driven without prior drilling. For more in-depth details on nailed connection specimen fabrication, the reader is referred to Chapter 3.

4.2.1 – Gypsum wallboard Connections

Gypsum wallboard connections were fabricated with gypsum wallboard from three different sources and two nail types. In all cases, the observed mode at yield was initially Mode I_s. Due to compaction of the side member material under the fastener at higher deflections (Figure 4.1), however, increases in bearing resistance at greater connection slip often resulted in the formation of a plastic hinge within the dowel, thereby exhibiting characteristics of Mode III_s yield (Figure 4.2). This phenomenon was observed in many of the gypsum wallboard and fiberboard connections and always involved a shift from Mode I_s to III_s. It will from here on be referred to as the "shifting mode phenomenon" or simply a "mode shift." The percentages of connections that underwent such a mode shift between yield and capacity are given for each connection set in Table 4.1.

Average resistance per connection set ranged from 44 to 66 pounds at 5% offset yield and from 80 to 119 pounds at capacity. The COVs associated with gypsum wallboard connection resistance were between 7.4% and 17.9% at 5% offset yield and between 5.0% and 13.2% at capacity. Averages and COVs at 5% offset yield and capacity for all six gypsum wallboard connection sets are given in Table 4.2. It should be noted that resistance COVs are consistently lower at capacity than at 5% offset yield.

Figure 4.1: Gypsum wallboard connection test in progress; nail head exhibiting the onset of mode shift.

Figure 4.2: Typical post-test fastener condition in connections that exhibited mode shift (left), and those that did not (right).

Table 4.1: Percentages of gypsum wallboard connections in which mode shift was observed.

	Mill Letter Designation		
	E	F	G
$1^3/_8$" Drywall Nail	100%	100%	100%
Roofing Nail	100%	38%	25%

Table 4.2: Average resistances and associated COVs at 5% offset yield and capacity for gypsum wallboard connections (resistance measurements in pounds).

			Mill E	Mill F	Mill G
5% Offset Yield	$1^3/_8$" Drywall Nail	Average	52	47	44
		COV	11.9%	17.9%	8.5%
	Roofing Nail	Average	66	55	60
		COV	10.9%	16.8%	7.4%
Capacity	$1^3/_8$" Drywall Nail	Average	103	86	80
		COV	5.9%	13.2%	5.0%
	Roofing Nail	Average	119	87	84
		COV	6.2%	13.0%	6.0%

Gypsum wallboard connections underwent relatively ductile load-slip response, with average ductility ratios ranging from 18 to 27. No significant trends in ductility ratios were noted with respect to nail diameter or gypsum wallboard source. Due to the fact the failure rates (i.e., percentage or fraction of those connections within each set that reached failure, as defined in Section 3.7) were less than or equal to 33.3 % in five out of the six gypsum wallboard sets, it is likely that their associated average ductility ratios would have been higher had the connections been subjected to greater deflections. Failure rates, average loads and displacements at failure (or the point where the test had to be stopped due to limitations on the range of the actuator), elastic stiffnesses, and ductility ratios for each of the six gypsum wallboard connection sets are presented in Table 4.3. This table presents values by the alpha-numeric identification system discussed in section 3.1.1, with the exception that the last two digits (those identifying the specimen number within the set) are not included because each row in the table contains values for an entire set, not just one specimen. Average load-displacement plots for each of the six gypsum wallboard connection sets are shown in Figure 4.3. These average load-displacement functions were calculated using the load-displacement functions of the individual connections from the given connection set. More specifically, this was done by taking the average resistance at finite values of displacement for all connections within the set. Figure 4.4 contains the average normalized load-deflection plots for both 1 $^{3}/_{8}$" drywall nail connections and roofing nail connections. Each load-displacement function in Figure 4.4 is normalized with respect to its own maximum, or capacity. In other words, values for the range are expressed as a percentage of connection capacity for the average load-displacement function. Note that the region in which first local maxima

Table 4.3: Failure rate, average elastic stiffness, ductility ratio, and load and displacement at failure for gypsum wallboard connection sets.

Series	Failure Rate	At Failure		Elastic Stiffness (lb/in)	Ductility Ratio
		Load (lb)	Disp (in)		
GE5	56.3%	85	0.884	2475	26
GER	12.5%	105	0.766	2531	20
GF5	17.6%	74	0.911	1989	25
GFR	6.3%	76	0.732	1676	18
GG5	25.0%	69	0.800	1923	25
GGR	33.3%	70	0.698	2290	27

occur is, on average, between 0.10” and 0.15” of connection slip. Resistances corresponding to these maxima are typically centered around 90% of capacity. See Section 3.7 for a definition and discussion of the first local maximum.

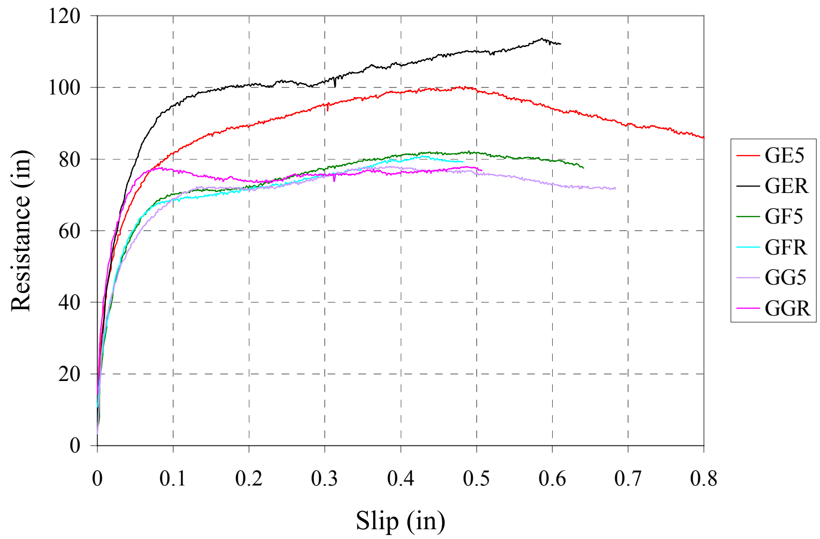

Figure 4.3: Average load-deflection plots for each of the six gypsum wallboard connection sets.

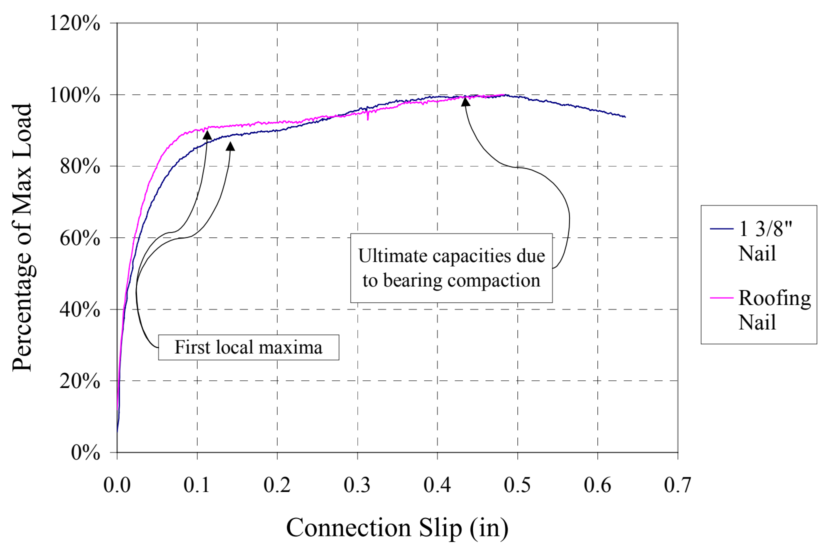

Figure 4.4: Normalized average load-deflection plots for both nail types used in gypsum wallboard connections.

Although two nail types were used in the fabrication of these connections (1 $^{3}/_{8}$” drywall nails and 1 ½” roofing nails), the most influential variable in overall connection behavior was the side member material source. This is most likely due to the fact that gypsum wallboard from Mill E contained embedded fibers as shown in Figure 4.5, while gypsum wallboard from the other two sources did not contain these fibers. The presence of these embedded fibers appears to have increased average resistances. This is evidenced by the fact that connections with drywall from Mill E afforded significantly greater resistances than other drywall connections (Table 4.2). These connections also had a greater tendency to undergo a mode shift between yield and capacity (Table 4.1), and exhibited greater initial elastic stiffness (Table 4.3).

Figure 4.5: Embedded fibers within gypsum wallboard from Mill E.

4.2.2 – Fiberboard Connections

Fiberboard connection specimens had side members from *four* different sources and were fabricated using either 6d box nails or 8d common nails. Just as for the gypsum wallboard connections, initial yield modes observed in fiberboard connection specimens were all Mode I_s. Mode shift occurred predominantly within those connections fabricated with 6d box nails, due to their lower dowel plastic bending moment. Relative percentages of connections that underwent mode shift for each fiberboard set are given in Table 4.4.

Table 4.4: Percentages of fiberboard connections in which mode shift was observed.

	Mill Letter Designation			
	A	B	C	D
6d Box Nail	94%	100%	100%	100%
8d Common Nail	0%	17%	0%	38%

While resistances afforded by fiberboard connections at 5% offset yield were slightly lower, fiberboard *capacities* were comparable to those of gypsum wallboard connections. Average connection resistances at 5% offset yield were between 33 to 60 pounds. These same connections ranged from 79 to 109 pounds at capacity. Associated COVs ranged from 6.3% to 13.8% at 5% offset yield and 4.1% to 9.1% at capacity. Average resistances and associated COVs at 5% offset yield, first local maximum, and capacity are given for all eight fiberboard connection sets in Table 4.5. Again, it should be noted that resistance COVs for these fiberboard connections are lower at capacity than at 5% offset yield.

Table 4.5: Average resistances and associated COVs at 5% offset yield and capacity for fiberboard connections (resistance measurements in pounds).

			Mill A	Mill B	Mill C	Mill D
5% Offset Yield	6d Box Nail	Average	33	35	36	45
		COV	6.3%	8.4%	13.2%	12.1%
	8d Common Nail	Average	48	51	41	60
		COV	13.8%	9.7%	10.8%	10.4%
Capacity	6d Box Nail	Average	80	81	79	95
		COV	8.0%	4.1%	9.1%	7.7%
	8d Common Nail	Average	93	109	98	102
		COV	6.7%	4.6%	6.9%	7.8%

Like gypsum wallboard connections, fiberboard connections exhibited relatively ductile load-slip response. Observed ductility ratios were greater for those connections having 8d common nails than for those having 6d box nails. This is explained simply by the fact that connections with 8d nails had greater elastic stiffness for all mill sources, thereby resulting in lower deflection at the equivalent energy yield point. At less than 10% in all but series FD6, failure rates were very low. Because of this, ductility ratios would presumably be much higher had greater connection slips been attainable during testing. Had this been the case, the apparent difference in ductility ratios between connections with different nail types would have most likely been eliminated. Table 4.6 contains elastic stiffnesses, failure rates, average resistance, deflection and energy up to failure, and ductility ratios for fiberboard connection sets. Average load-deflection plots of the eight fiberboard connection sets are shown in Figure 4.6. Normalized load-deflection plots with respect to capacity are shown for both 6d box nail connections and 8d common nail connections in Figure 4.7.

Table 4.6: Failure rate, average elastic stiffness, ductility ratio, and load and displacement at failure for fiberboard connection sets.

Series	Failure Rate	At Failure		Elastic Stiffness (lb/in)	Ductility Ratio
		Load (lb)	Disp (in)		
FA6	6.3%	74	0.811	1310	16
FA8	6.3%	88	0.826	2050	23
FB6	0.0%	76	0.831	1151	14
FB8	6.7%	102	0.804	2039	18
FC6	0.0%	77	0.833	1359	17
FC8	0.0%	95	0.832	1756	19
FD6	12.5%	82	0.787	1443	15
FD8	0.0%	95	0.833	2697	25

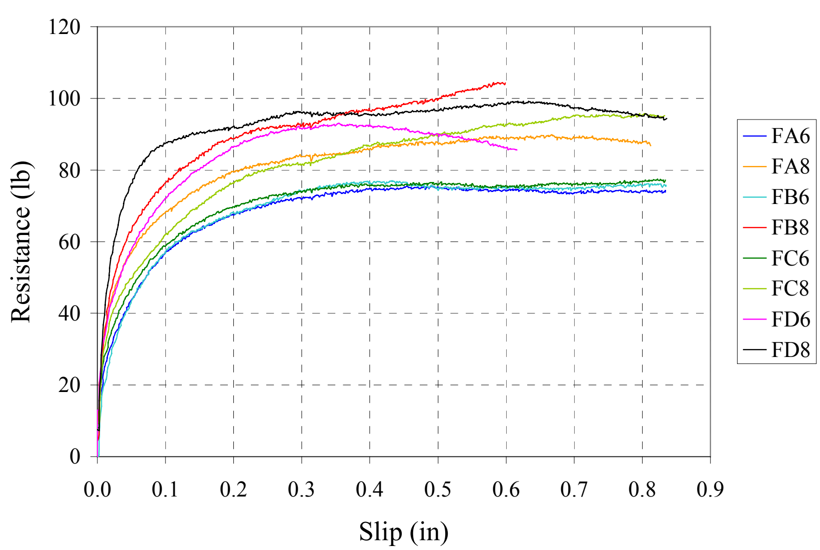

Figure 4.6: Average load-deflection plots for each of the eight fiberboard connection sets.

A visual comparison of the load-deflection plots in Figures 4.6 and 4.7 reveals that connections fabricated with 8d common nails typically reached their capacities at greater deflections than did those with 6d box nails. This is due to the fact that connections with 8d nails usually exhibited Mode I_s yield characteristics throughout the entire test, whereas those with 6d nails almost always underwent a mode shift. Thus, the factor limiting resistance in connections with 8d nails was the side member bearing resistance, which increased with displacement due to bearing densification. In those connections with 6d nails, however, the limiting factor for resistance at high displacement was primarily that of the dowel plastic moment.

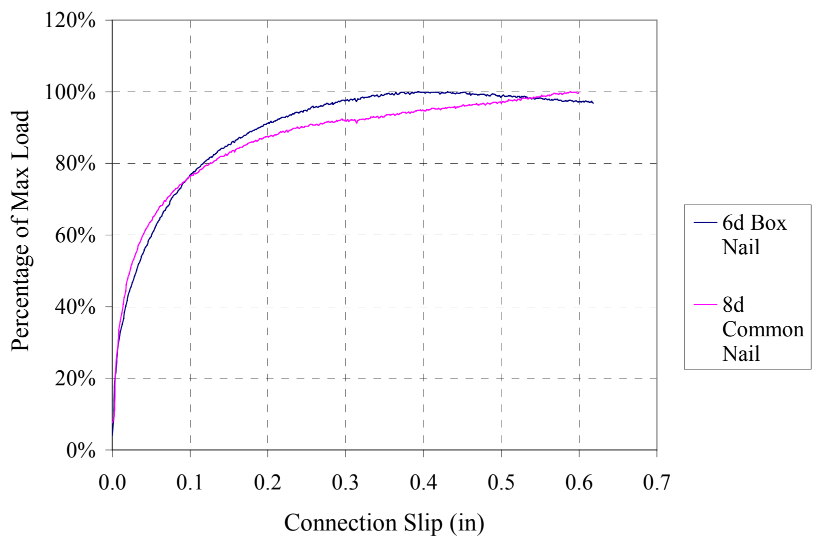

Figure 4.7: Normalized average load-deflection plots for both nail types used in fiberboard connections.

4.2.3 – Hardboard Connections

Side members of hardboard connections were obtained from one of three mill sources. Two nail types, 6d box and 8d common, were also used in these connections' fabrication. Due to the much higher density of hardboard, observed yield modes were, in all cases, characteristic of Mode III_s. Thus, these connections provided between 2.5 and 4.0 times the resistance of gypsum wallboard and fiberboard connections.

Average connection resistances ranged from 100 to 190 pounds at 5% offset yield and from 211 to 395 pounds at capacity. COVs were between 8.7% and 17.5% at

5% offset yield and between 8.3% and 18.1% at capacity. These, in addition to the averages and COVs at 5% offset yield and capacity for all other hardboard connection sets are given in Table 4.7. Note that, in the case of hardboard connections, there is no apparent trend in terms of COVs between resistances at 5% offset yield and those at capacity.

Table 4.7: Average resistances and associated COVs at 5% offset yield and capacity for hardboard connections (resistance measurements in pounds).

			Mill H	Mill I	Mill J
5% Offset Yield	6d Box Nail	Average	100	117	118
		COV	11.1%	12.2%	17.5%
	8d Common Nail	Average	176	169	190
		COV	8.7%	10.8%	10.7%
Capacity	6d Box Nail	Average	211	237	253
		COV	8.3%	12.3%	18.1%
	8d Common Nail	Average	371	324	395
		COV	9.6%	11.1%	12.7%

Subtle differences in connection response with respect to side member material source were apparent. Connections fabricated with material from Mill J, for example, afforded the greatest resistance, especially at capacity. Those connections having the greatest average elastic stiffness were the ones fabricated with material from Mill I. Due to the relatively high variability associated with elastic stiffness, however, it is not known whether these trends are significant.

While side member material source did have an affect on hardboard connection resistances, the greatest influence on connection response was nail type. Connections fabricated with 8d common nails afforded significantly greater resistances at both 5% offset yield and capacity. This can clearly be seen in both Table 4.7, mentioned previously, and Figure 4.8, which shows the average load-deflection plots for each of the six hardboard connections. Elastic stiffnesses were also consistently higher in connections with 8d nails. This significant increase in both resistance and stiffness with respect to nail diameter can be explained by the fact that these connections all exhibited Mode III_S yield, and thus their behaviors were highly dependent upon the material and section properties of the nail.

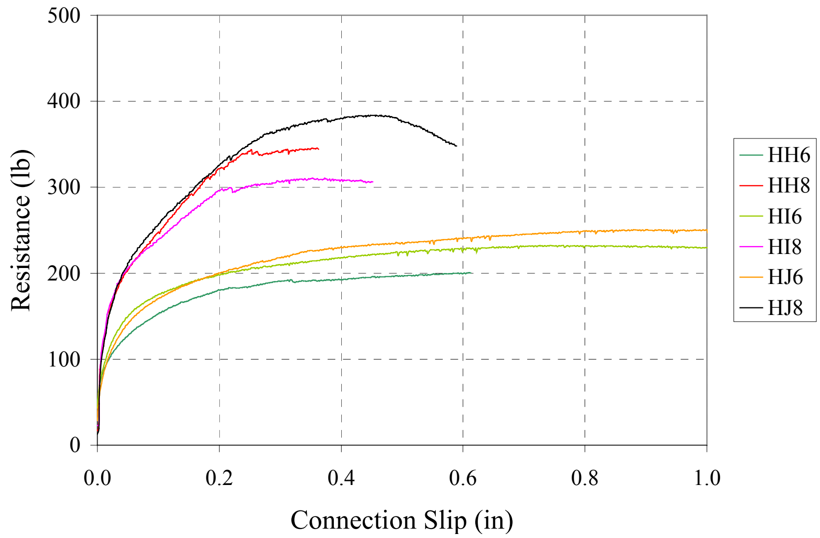

Figure 4.8: Average load-deflection plots for each of the six hardboard connection sets.

Although all hardboard connections exhibited Mode III_s yield, those with 6d box nails had significantly greater ductility than those fabricated with 8d common nails. This difference is primarily due to the fact that connections with 8d nails usually failed at around 0.50” whereas *none* of the 6d box nail connections failed at the maximum attainable connection slip of 1.00”. It should be noted that, because none of them reached failure during testing, the actual ductility ratios of connections having 6d box nails are most likely even greater than those observed. Such high ductilities are attributable to these connections’ Mode III_s yield, in which much of the mechanical energy is absorbed by plastic bending in the ductile steel nail. The comparatively high ductility of connections having 6d box nails is reflected in the fact that their average observed energies up to failure are comparable to those of connections with 8d nails. It is likely, in fact, that these 6d nailed connections would have displayed *greater* energy dissipation capabilities than connections with 8d nails had the tests been run to greater deflections.

The failure rates of hardboard connections with 8d nails were between 65% and 75%. This high failure rate was brought about by the fact that the ultimate bearing strength of hardboard was often exceeded in 8d nailed connections at slips of greater than 0.40”, thereby resulting in crushing of the hardboard material. This bearing failure and associated material crushing is illustrated in Figure 4.9. Table 4.8 contains the elastic stiffness, failure rate, average resistance, deflection and energy up to failure, and ductility ratio for each of the six hardboard connection sets.

Figure 4.9: Crushed material at bearing interface in hardboard connection.

Table 4.8: Failure rate, average elastic stiffness, ductility ratio, and load and displacement at failure for hardboard connection sets.

Series	Failure Rate	At Failure		Elastic Stiffness (lb/in)	Ductility Ratio
		Load (lb)	Disp (in)		
HH6	0.0%	203	0.962	3981	25
HH8	64.7%	307	0.671	6764	14
HI6	0.0%	230	0.999	4235	24
HI8	75.0%	262	0.669	7455	19
HJ6	0.0%	250	0.999	3612	19
HJ8	68.8%	323	0.725	6212	14

4.2.4 – Oriented Strand Board and Plywood Connections

Test variables for OSB and plywood connections included side member thickness ($^{7}/_{16}$" and $^{23}/_{32}$" for OSB and $^{3}/_{8}$" and ¾" for plywood) and nail type (8d, 10d, and 16d common nails). Unlike the gypsum wallboard, fiberboard, and hardboard connections, side member materials for OSB and plywood connections were obtained from only one source per material type. Thus, since material source was not a test variable, specific manufacturer identities were not recorded.

Observed yield modes were either Mode III_s or Mode IV in all cases. Connections having $^{7}/_{16}$" OSB and $^{3}/_{8}$" plywood side members yielded in Mode III_s while those having side members of $^{23}/_{32}$" OSB and ¾" plywood yielded predominately in Mode IV.

Average OSB connection resistances ranged from 126 to 213 pounds at 5% offset yield and from 212 to 400 pounds at capacity. Resistance COVs for these connection sets ranged from 15.9% to 19.9% at 5% offset yield and from 12.2% to 27.8% at capacity. In general, COVs for resistance of OSB connections were greater for those connections having larger nail diameters. Plywood connection resistances averaged between 115 and 229 pounds at 5% offset yield and between 207 and 444 pounds at capacity. COVs for the resistance of these connections ranged from 11.0% to 14.6% at 5% offset yield and from 13.1% to 18.3% at capacity. Note that plywood connections had significantly lower COVs associated with resistances at 5% offset yield than at capacity, whereas the opposite is true of the OSB connections (Table 4.9).

Table 4.9: Average resistances and associated COVs at 5% offset yield and capacity for OSB and plywood connections (resistance measurements in pounds).

			Side Member Material			
			$^{7}/_{16}$" OSB	$^{3}/_{8}$" Plywood	$^{23}/_{32}$" OSB	$^{3}/_{4}$" Plywood
5% Offset Yield	8d Common Nail	Average	126	115		
		COV	19.2%	11.0%		
	10d Common Nail	Average	159	155	184	199
		COV	19.9%	14.6%	15.9%	12.2%
	16d Common Nail	Average			213	229
		COV			17.3%	12.7%
Capacity	8d Common Nail	Average	212	207		
		COV	12.2%	13.1%		
	10d Common Nail	Average	273	306	364	381
		COV	13.7%	20.1%	22.9%	18.3%
	16d Common Nail	Average			400	444
		COV			27.8%	17.8%

All OSB and plywood connections had relatively high ductility ratios. Average ductility ratios ranged from 17, corresponding to 10d nailed connections having $^{3}/_{8}$" plywood side members, to 35, corresponding to 8d nailed connections with $^{7}/_{16}$" OSB side members. No significant trends in connection ductility were apparent with respect to either side member thickness, material type, or nail type, as associated COVs were high (i.e., 25% to 65%). Trends in failure rates, however, were observed with respect to side member thickness. Failure rates in connections with thin side members ($^{7}/_{16}$" OSB and $^{3}/_{8}$" plywood) ranged between 29% and 59%, while those for connections with thick side members ($^{23}/_{32}$" OSB and $^{3}/_{4}$" plywood) were consistently under 10%. Failure mechanisms of connections with both thin and thick side members involved a combination fastener withdrawal and crushing of the material within the side member. Connection failure rates, along with ductility ratios, and average resistance, deflection and energy up to failure for OSB and plywood connections are given in Table 4.10. It should be noted that connection configurations having low failure rates were the ones in which Mode IV yield was exhibited.

Table 4.10: Failure rate, average elastic stiffness, ductility ratio, and load and displacement at failure for OSB and plywood connection sets.

Nail Type	Side Member	Failure Rate	At Failure		Elastic Stiffness (lb/in)	Ductility Ratio
			Load (lb)	Disp (in)		
8d Common	$^{7}/_{16}$" OSB	29%	182	1.022	4914	35
	$^{3}/_{8}$" Plywood	50%	168	0.700	5245	24
10d Common	$^{7}/_{16}$" OSB	47%	229	0.873	5753	27
	$^{23}/_{32}$" OSB	6%	344	1.441	5671	28
	$^{3}/_{8}$" Plywood	59%	262	0.837	5176	17
	$^{3}/_{4}$" Plywood	6%	357	1.456	5346	25
16d Common	$^{23}/_{32}$" OSB	7%	376	1.175	5371	21
	$^{3}/_{4}$" Plywood	0%	441	1.194	6647	24

Overall, resistances afforded by OSB connections were comparable to those of plywood connections. Differences between the resistances afforded by OSB and plywood were only evident between the capacity loads of connections with relatively large ratios of nail diameter-to-side member thickness. In these cases, the capacity resistances of plywood connections were approximately 10% to 12% greater than those of OSB, as can be seen in Table 4.9.

Load-response characteristics were highly dependent upon side member thickness for both OSB and plywood connections. Connections with thin side members tended to reach their capacities earlier than connections with thick side members. Note that similarities between connections with similar side member thickness are tied closely to failure rates, and may be explained by the fact that connections with thin side members yielded predominantly by Mode III_s, while those with thick side members exhibited Mode IV yield. Connections yielding by Mode IIIs typically failed through withdrawal of the nail from the main member, as did the handful of Mode IV connections that failed during testing. Average load-deflection plots for each of the OSB and plywood connection sets are presented in Figures 4.10 and 4.11, respectively. Illustrating differences in connection slip at capacity, Figure 4.12 contains the average normalized load-deflection curves for each of the two yield modes observed in OSB and plywood connections.

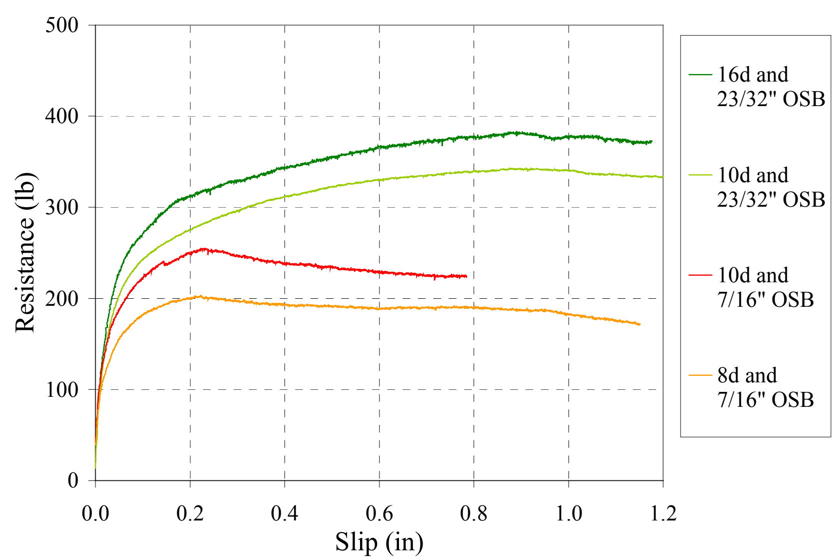

Figure 4.10: Average load-deflection plots for each of the four OSB connection sets. The green and light green curves (top) are of connections that yielded by Mode IV and rarely reached failure. The red and orange curves (bottom) are of connections that yielded by Mode III_s and usually failed by fastener withdrawal.

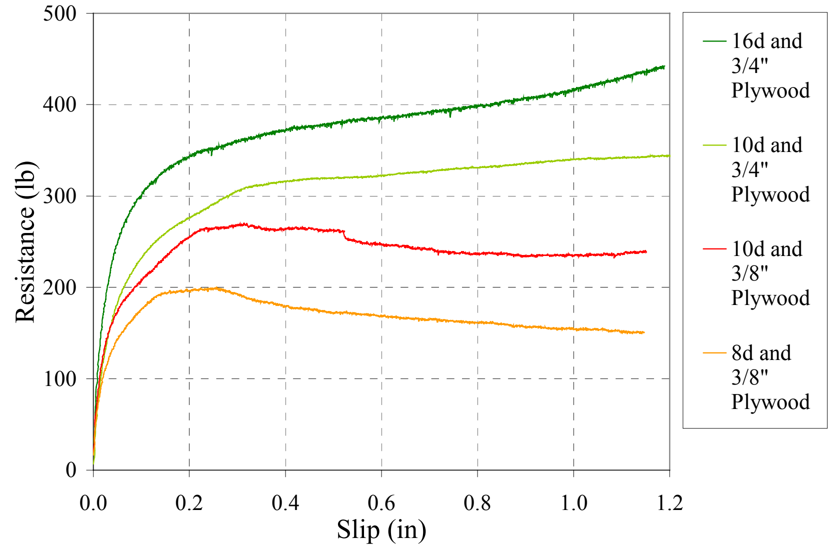

Figure 4.11: Average load-deflection plots for each of the four plywood connection sets. The green and light green curves (top) are of connections that yielded by Mode IV and rarely reached failure. The red and orange curves (bottom) are of connections that yielded by Mode III_s and usually failed by fastener withdrawal.

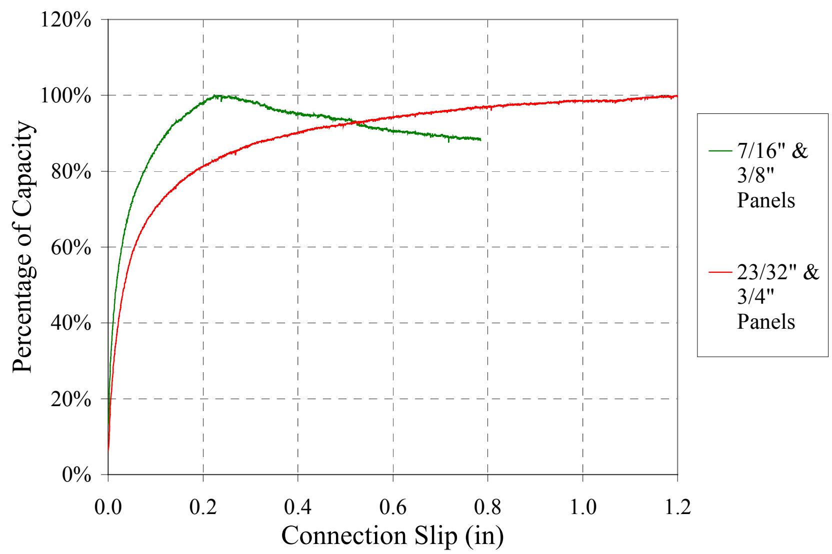

Figure 4.12: Normalized average load-deflection plots for OSB and plywood connections having thick side members (red curve, exhibiting Mode IV) versus those having thin side members (green curve, exhibiting Mode III_s). Differences in deflection at capacity are illustrated.

4.2.5 – Solid Wood Nailed Connections

Nailed connections having solid wood main and side members were constructed to simulate typical connections between framing members in light-frame construction. Two sets, a total of thirty connections, were tested. The only difference between these two configurations was commercial species grouping (see Section 3.2.2). All were fabricated with 16d common nails and had 2x4 main and side members.

Solid wood nailed connections yielded by Mode IV in all cases. Figure 4.13 illustrates Mode IV as observed in a Southern Pine connection.

Figure 4.13: Mode IV yield observed in solid wood nailed connections.

Resistances at both 5% offset yield and capacity were comparable, on average, to the same parameters for $^{23}/_{32}$" OSB and ¾" plywood connections fabricated with 16d nails. While overall differences between SPF and Southern Pine connections were small, connections of the latter mentioned set tended to provide greater resistance at 5% offset yield, while the opposite was true of resistances at capacity. Mean (average) resistances afforded at 5% offset yield were 204 and 211 pounds for SPF and Southern Pine connections, respectively. At capacity, the same sets averaged 410 and 383 pounds. COVs corresponding to these values were 12.3% and 14.5% at 5% offset yield and 18.2% and 13.2% at capacity for SPF and Southern Pine connections, respectively.

Resistances and associated COVs at 5% offset yield and capacity are given in Table 4.11.

Table 4.11: Average resistances and associated COVs at 5% offset yield and capacity for solid wood nailed connections (resistance measurements in pounds).

<table>
<tr><th colspan="2"></th><th>SPF</th><th>SYP</th></tr>
<tr><td rowspan="2">5% Offset Yield</td><td>Average</td><td>204</td><td>211</td></tr>
<tr><td>COV</td><td>12.3%</td><td>14.5%</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td rowspan="2">Capacity</td><td>Average</td><td>410</td><td>383</td></tr>
<tr><td>COV</td><td>18.2%</td><td>13.2%</td></tr>
</table>

None of the solid wood nailed connections reached failure during testing. These connections typically afforded above 90% of their respective capacities even at relatively high deflections (up to the displacement limit allowed by the actuator) due to a combination of the resistance provided by nail withdrawal and continued Mode III_s yielding. In light of this, it may be assumed that the average measured ductility ratios of 23.0 and 28.1 for SPF and Southern Pine, respectively, are lower than those that would have been measured had higher deflections been attainable. The lower ductility ratios measured in SPF connections are a reflection of the fact that these connections typically had lower initial elastic stiffness than Southern Pine connections which translated into larger yield displacements. These average stiffness values, along with ductility ratios, failure rates, and resistance and deflection at failure are given in Table 4.12.

Table 4.12: Failure rate, average elastic stiffness, ductility ratio, and load and displacement at failure for solid wood nailed connection sets.

Species Grouping	Failure Rate	At Failure		Elastic Stiffness (lb/in)	Ductility Ratio
		Load (lb)	Disp (in)		
SPF	0.0%	396	1.352	5844	23
SYP	0.0%	371	1.182	7844	28

Average load-deflection curves were consistent in shape with those observed for the other connection configurations that yielded by Mode IV (i.e., $^{23}/_{32}$" OSB and ¾" plywood connections). Plots of these curves are shown in Figure 4.14.

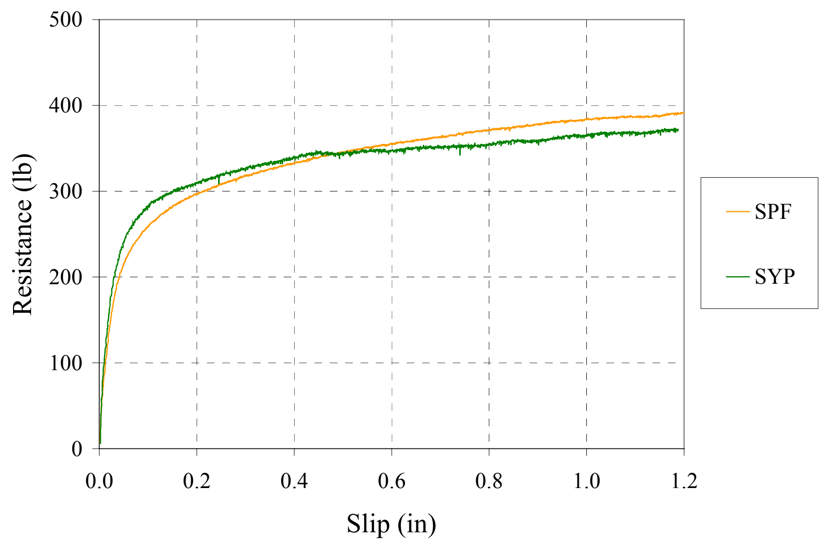

Figure 4.14: Average load-deflection plots for solid wood, nailed connection sets.

4.2.6 – Capacity Resistance vs. 5% Offset Yield Resistance in Nailed Connections

The scatter plot in Figure 4.15 illustrates the relationship between the resistance provided at capacity versus that provided at 5% offset yield. Data corresponding to each individual nailed connection is included here. A least squares linear regression is fitted to the data such that it intercepts the y-axis at zero. This regression suggests that the capacities of nailed connections are typically around 1.9 to 2.0 times their 5% offset yield resistance. It is expressed by the following equation:

$$P_{ult} = 1.934 P_{5\%OY} \tag{4.1}$$

where P_{ult} is the connection resistance at capacity and $P_{5\%OY}$ is the resistance at 5% offset yield. The associated R-squared value for this regression is 0.9439, indicating a strong correlation, as expected.

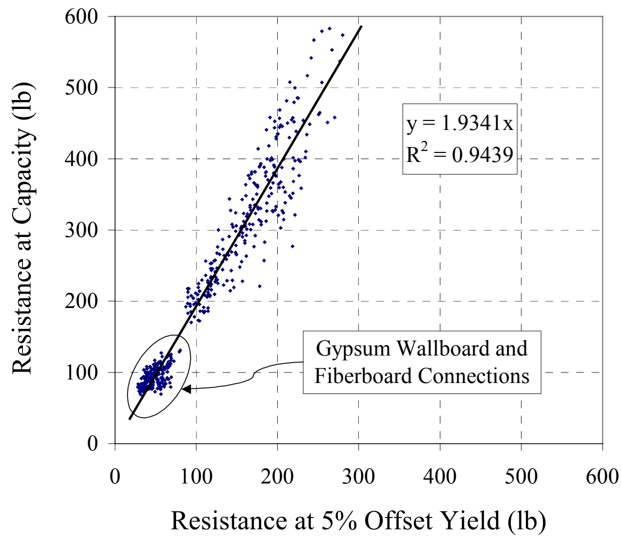

Figure 4.15: Scatter plot of observed capacity resistance vs. 5% offset yield resistance for all nailed connections.

4.3 – Bolted Connection Tests

A total of one-hundred-ninety-nine bolted connection tests (grouped in twelve sets) were conducted. All bolted connections had solid wood main and side members cut from either 2x4 or 4x4 nominal dimension lumber. Thus, one of the test variables was main member bearing length. Other test variables included commercial species group of the lumber and bolt diameter.

Observed yield modes were, for the most part, either Mode II or III_s (Figures 4.16 and 4.17). In a few specimens, however, Mode IV was observed (Figure 4.18). Yield Mode II was observed in all connections having $^5/_8$" diameter bolts. For those connections fabricated with ½" diameter bolts, Mode III_s prevailed in connections with 4x4 main members, while Mode II was observed in connections where both members were cut from 2x4 material. In general, the same yield mode trends were noted in connections having $^3/_8$" diameter bolts as were for those having ½" bolts. Due to the much lower plastic bending moment of $^3/_8$" bolts, however, connections having Southern Pine 2x4 side members often exhibited yielding characteristics of Modes II, III_m, and/or III_s. Observed yield modes for each of the twelve bolted connection sets are presented in Table 4.13. The predominant yield mode for each set is given in bold print. For sets in which multiple yield modes were observed, the non-predominant modes are given in regular print.

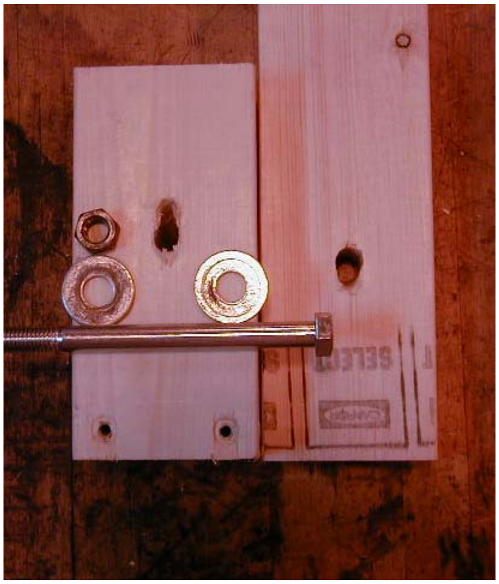

Figure 4.16: Typical post-test condition of bolted connections yielding by Mode II.

Figure 4.17: Typical post-test condition of bolted connections yielding by Mode III.

Figure 4.18: Typical post-test condition of bolted connections yielding by Mode IV.

Table 4.13: Yield modes observed in each bolted connection set.

		Bolt Diameter		
		$^3/_8$"	$^1/_2$"	$^5/_8$"
Main Member	SPF 2x4	**II**	**II**	**II**
Main Member	SYP 2x4	**II**, III, IV	**II**	**II**
Main Member	SPF 4x4	**III**	II, **III**	**II**
Main Member	SYP 4x4	**III**, IV	**III**	**II**

Note: The predominant yield mode for each set is given in bold print.

Resistances afforded by bolted connections were affected by bolt diameter, as well as configuration and species grouping of the main and side members. Average resistances at 5% offset yield ranged from just under 1,000 pounds, for $^{3}/_{8}$” bolted connections having 2x4 SPF main members, to around 2,450 pounds, for $^{5}/_{8}$” bolted connections having 2x4 Southern Pine main members. Average capacity resistances ranged from just under 1,700 pounds for $^{3}/_{8}$” bolted connections having simulated 4x4 SPF main members, to just under 4,400 pounds for $^{5}/_{8}$” bolted connections having 2x4 Southern Pine main members. Connections with 2x4 Southern Pine main members provided the highest resistance values at capacity for all bolt diameters. Two reasons for this are: 1) Southern Pine 4x4 material used for connection fabrication had much lower average embedment strength than Southern Pine 2x4 material, thereby negating the potential increase that would otherwise be brought about by longer bearing length, and 2) the shorter bolt length in connections with 2x4 main members caused a greater amount of rigid Mode II bolt rotation, thereby increasing the tension component within the bolt, as well as friction between the two members. The latter of these factors also explains why connections with 2x4 SPF main members often afforded greater resistance at capacity than those having simulated 4x4 SPF main members. COVs corresponding to resistance values were lower for bolted connections than they were for nailed connections. Resistance values at 5% offset yield had associated COVs ranging from 6.4% to 14.4%. COVs of resistance at capacity were between 6.7% and 14.6%. Average bolted connection resistance and associated COVs at both 5% offset yield and capacity are given in Table 4.14.

Ductility ratios of bolted connections averaged between 2.7 and 4.1 with COVs ranging from 9.5% to 23.5%. No notable trends in ductility ratios were evident with respect to either bolt diameter, main member thickness, or commercial species group. Failure rates ranged between 0% and 71%, and increased with respect to bolt diameter. It was additionally noted that failure rates were generally higher in connections with SPF members. These failure rates, although relatively high for some sets, most likely had minimal impact on ductility ratios due to the fact that failures usually occurred at higher connection slip values (slips of between 0.75” and 1.00”). Elastic stiffness values range from around 5,000 to just over 20,000 pounds per inch. These increased with respect to bolt diameter and were also typically higher in connections with southern pine members. Average stiffness values for bolted connections, along with ductility ratios, failure rates, and resistance and deflection at failure are given in Table 4.15.

Table 4.14: Average resistances and associated COVs at 5% offset yield and capacity for bolted connections (resistance measurements in pounds).

			Side Member Material			
			SPF 2x4	SPF 4x4	SYP 2x4	SYP 4x4
5% Offset Yield	3/8" Bolt	Average	999	1038	1100	1163
		COV	10.5%	11.0%	14.4%	10.3%
	1/2" Bolt	Average	1496	1634	1669	1712
		COV	7.0%	7.9%	10.7%	13.1%
	5/8" Bolt	Average	1811	2257	2441	2333
		COV	6.4%	10.7%	8.6%	13.0%
Capacity	3/8" Bolt	Average	1924	1682	2195	2003
		COV	9.9%	10.0%	14.6%	7.5%
	1/2" Bolt	Average	2627	2555	3134	2894
		COV	10.2%	6.7%	12.4%	13.6%
	5/8" Bolt	Average	3126	3644	4383	3730
		COV	7.3%	7.7%	8.0%	14.0%

Average load-slip plots for each connection configuration are illustrated in Figures 4.19 through 4.22. Each of these figures shows data for one main and side member configuration (e.g., SPF 2x4-to-SPF 2x4). Normalized load-slip curves for these bolted connections indicate no trends in response characteristics with respect to bolt diameter (Figure 4.23). A slight difference in load-slip curves is apparent, however, with respect to species group. This can be seen in Figure 4.24 where Southern Pine connections exhibit greater normalized elastic stiffness.

Table 4.15: Failure rate, average elastic stiffness, ductility ratio, and load and displacement at failure for bolted connection sets.

Bolt Diameter	Main Member	Failure Rate	At Failure		Elastic Stiffness (lb/in)	Ductility Ratio
			Load (lb)	Disp (in)		
3/8"	SPF 2x4	19%	1800	0.927	5991	3.0
	SPF 4x4	0%	1665	0.958	5005	2.7
	SYP 2x4	0%	2190	0.971	7806	3.2
	SYP 4x4	0%	2000	0.969	9103	3.9
1/2"	SPF 2x4	27%	2452	0.905	14920	4.0
	SPF 4x4	18%	2425	0.937	8242	2.7
	SYP 2x4	25%	2974	0.923	12628	3.9
	SYP 4x4	6%	2853	0.934	13725	3.8
5/8"	SPF 2x4	18%	3000	0.905	10931	2.7
	SPF 4x4	71%	3093	0.751	13139	2.9
	SYP 2x4	6%	4285	0.935	17510	3.7
	SYP 4x4	29%	3405	0.852	20038	4.1

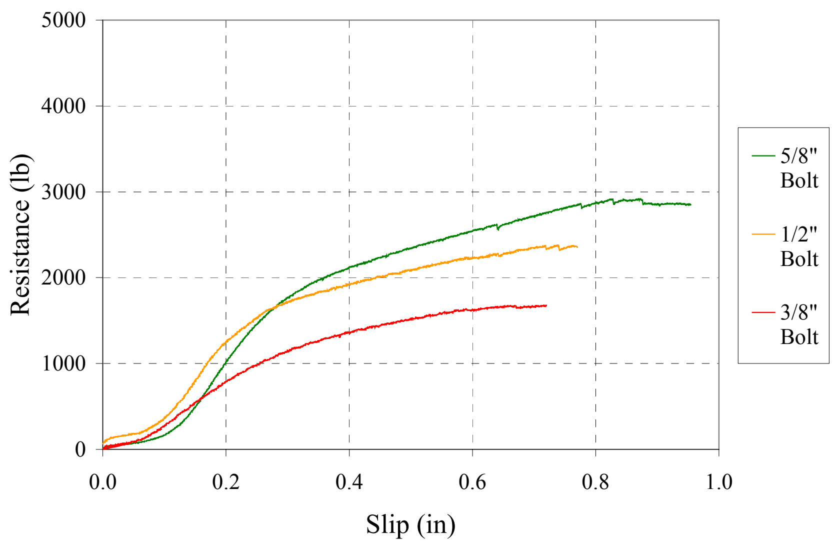

Figure 4.19: Average load-deflection plots for bolted connection sets having SPF 2x4 main members.

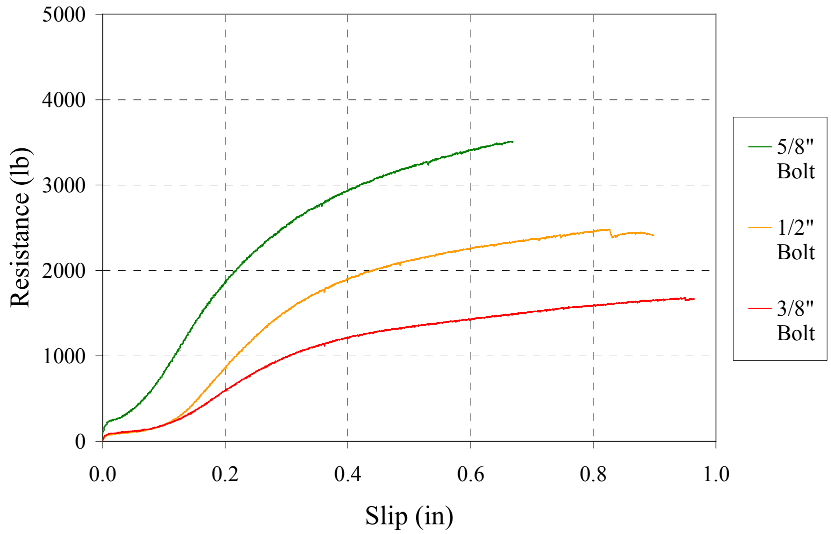

Figure 4.20: Average load-deflection plots for bolted connection sets having SPF 4x4 main members.

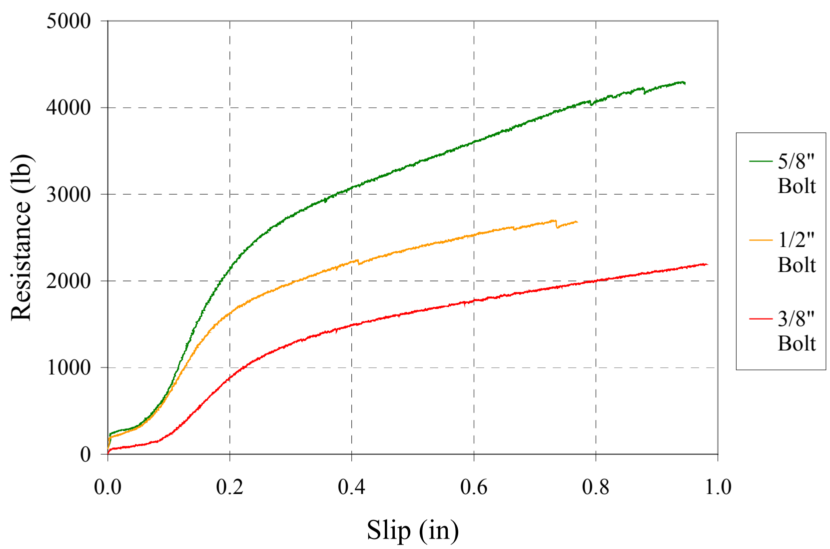

Figure 4.21: Average load-deflection plots for bolted connection sets having SPF 2x4 main members.

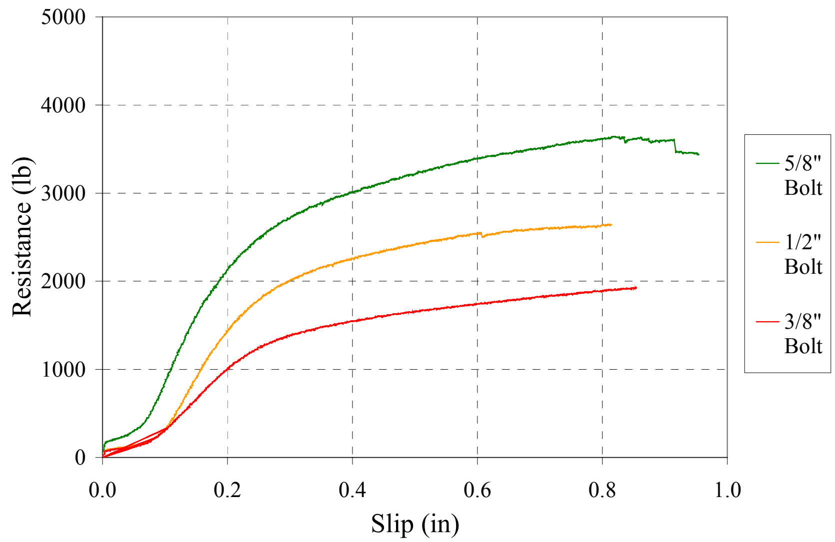

Figure 4.22: Average load-deflection plots for bolted connection sets having SPF 4x4 main members.

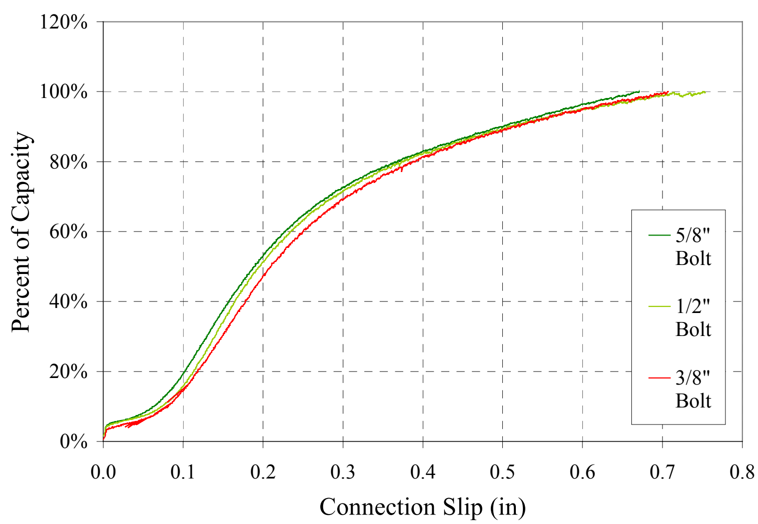

Figure 4.23: Normalized average load-deflection plots for bolted connections (averaged with respect to bolt diameter).

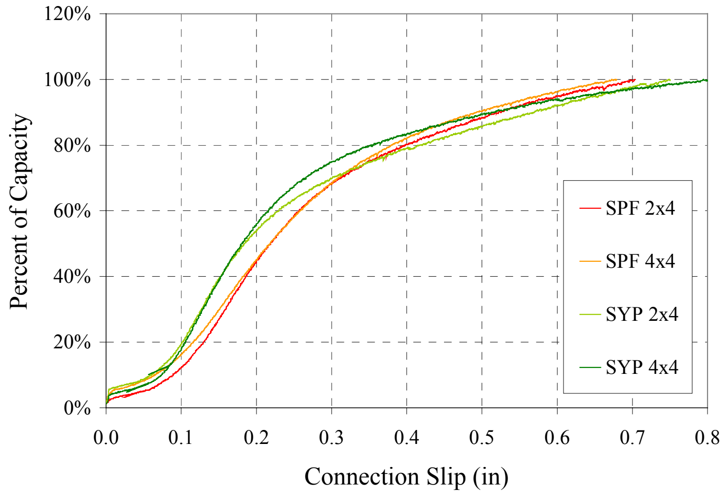

Figure 4.24: Normalized average load-deflection plots for bolted connections (averaged with respect to main member material type).

4.3.1 – Capacity Resistance vs. 5% Offset Yield Resistance in Bolted Connections

The relationship between resistance afforded at capacity versus that afforded at 5% offset yield is illustrated for each individual bolted connection in Figure 4.25. This regression suggests that the capacities of bolted connections are typically around 1.6 to 1.8 times their 5% offset yield resistance. The regression is expressed by the following equation:

$$P_{ult} = 1.706 P_{5\%OY} \tag{4.2}$$

This least-squares regression has an associated R-squared value of 0.8744. While this R-squared value is slightly less than the one associated with nailed connections, it still indicates a strong correlation between resistances at 5% offset yield and capacity. Nailed connection data is also plotted on this chart for easy comparison.

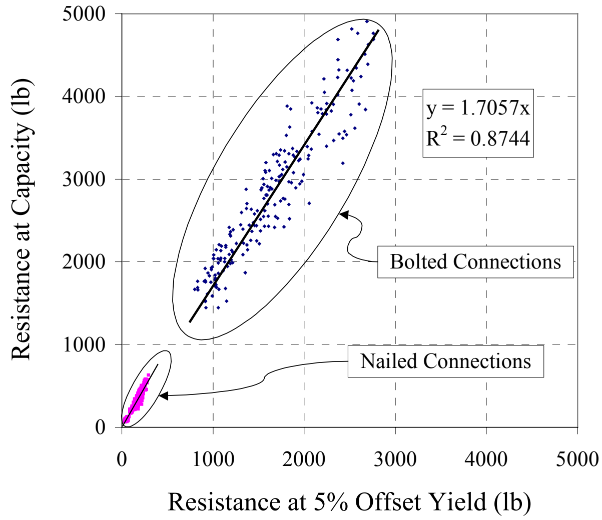

Figure 4.25: Capacity vs. 5% offset yield resistance for bolted connections.

4.4 – Embedment Tests

One embedment test was conducted on each member (main and side) of each connection specimen. Data gathered from these tests was used to determine embedment strengths at the 5% offset yield point as well as at capacity. Due to the fact that the program used for connection data analysis was also used for embedment data analysis (with minor modifications), all the parameters mentioned at the beginning of this chapter were also calculated for each embedment test. Embedment strengths, both at 5% offset yield and capacity, are discussed in the present section. These were calculated by dividing the resistances provided at both 5% offset yield and capacity by the product of the fastener diameter and the bearing length of the embedment specimen. Consequently, embedment strengths are expressed in units of pounds per square inch (psi). Tabulated embedment strengths of each member of each connection are given in Appendix C.

4.4.1 – Embedment Tests on Panel Products

As described in Section 3.3.3, side member embedment tests corresponding to panel-type connection specimens were conducted using one of two methods. These two methods were: 1) the full-hole method, used for gypsum wallboard and fiberboard specimens, and 2) the half-hole method, used for hardboard, OSB, and plywood specimens. Embedment strengths, as well as other test results, generated for these five material types are presented in this section.

Similar to the connection specimens from which they were cut, gypsum wallboard and fiberboard embedment specimens exhibited ductile load-deflection behavior. In fact, the failure rate was zero for all sets. Resistance values at both 5% offset yield and capacity were characterized by relatively low within-set variability. Between-set variability was higher due to the fact that materials were obtained from different sources.

Embedment strengths for gypsum wallboard under 1 $^3/_8$" drywall nails (ϕ = 0.099") averaged around 700 psi at 5% offset yield and 1410 psi at capacity. Under 1 ½" roofing nails (ϕ = 0.120"), 5% offset yield and capacity resistance values averaged approximately 640 psi and 1270 psi, respectively. For both nail diameters, specimens from Mill E provided the highest resistance values. The embedment strengths of these specimens were significantly higher than those of specimens from the other two mills. T-tests used for comparing equality of means had associated p-values (probability values) of less than 2×10^{-6} in all cases. This is probably due to the inclusion of fibers in the product and is reflected in the high connection resistance values, as is discussed in Section 4.2.1. Embedment strengths for fiberboard specimens were comparable to those of gypsum wallboard. Resistances under 6d box nails (having the same diameter, ϕ = 0.099", as 1 $^3/_8$" drywall nails) averaged approximately 820 psi at 5% offset yield and 1560 psi at capacity. Under 8d common nails (ϕ = 0.131"), these same values averaged approximately 630 psi and 1240 psi, respectively. As was the case for gypsum wallboard material, one of the fiberboard sources, Mill D, consistently proved to be an outlier in terms of embedment resistance. Average embedment strengths at both 5% offset yield and capacity, along with corresponding COVs, are given for gypsum wallboard in Table 4.16, and for fiberboard in Table 4.17.

Table 4.16: Average embedment strengths and associated COVs of gypsum wallboard (values in pounds per square inch).

			Mill E	Mill F	Mill G
5% Offset Yield	1 $^3/_8$" Drywall Nail	Average	830	656	618
		COV	10.4%	13.3%	5.2%
	Roofing Nail	Average	750	597	576
		COV	8.4%	13.6%	8.6%
Capacity	1 $^3/_8$" Drywall Nail	Average	1613	1352	1258
		COV	7.1%	9.9%	5.7%
	Roofing Nail	Average	1473	1217	1140
		COV	6.9%	11.7%	6.0%

Table 4.17: Average embedment strengths and associated COVs of fiberboard (values in pounds per square inch).

			Mill A	Mill B	Mill C	Mill D
5% Offset Yield	6d Box Nail	Average	695	850	697	1047
		COV	11.2%	11.0%	25.6%	21.7%
	8d Common Nail	Average	528	690	524	785
		COV	27.5%	18.4%	8.0%	16.5%
Capacity	6d Box Nail	Average	1412	1694	1360	1762
		COV	7.5%	9.2%	10.2%	12.8%
	8d Common Nail	Average	1200	1276	1105	1389
		COV	29.3%	8.0%	8.3%	8.3%

Due to their much higher density, hardboard specimens provided embedment strengths of approximately 5 to 7 times those of gypsum wallboard and fiberboard. Additionally, the load-deflection response of hardboard embedment tests was characteristically less ductile. Failure rates ranged from 18% to 94%. Hardboard from Mills H and I failed more often than hardboard from Mill J. Average hardboard embedment strength under 6d box nails was about 4910 psi at 5% offset yield and 9320 psi at capacity. Under 8d common nails, embedment strengths averaged 4160 psi at 5% offset yield and 6280 psi at capacity. As was the case in gypsum wallboard and fiberboard specimens, within-set variability was typically lower than between-set variability. Average hardboard embedment strengths at 5% offset yield and capacity are given for each of the six sets, along with corresponding COVs, in Table 4.18.

Table 4.18: Average embedment strengths and associated COVs of hardboard (values in pounds per square inch).

			Mill H	Mill I	Mill J
5% Offset Yield	6d Box Nail	Average	5046	3764	5921
		COV	19.8%	7.8%	20.5%
	8d Common Nail	Average	4119	4051	4300
		COV	16.9%	20.8%	16.1%
Capacity	6d Box Nail	Average	9126	7501	11335
		COV	6.5%	7.3%	11.7%
	8d Common Nail	Average	6265	5398	7186
		COV	7.2%	6.8%	10.5%

OSB and plywood embedment strengths ranged from 3300 psi to approximately 8400 psi at 5% offset yield, and from 5150 psi to approximately 11500 psi at capacity. Average OSB and plywood embedment strengths at 5% offset yield and capacity are given for each of the eight sets, along with corresponding COVs, in Table 4.19. As observed in other panel materials, embedment strengths at both 5% offset yield and capacity tended to decrease with respect to nail diameter. Plywood consistently provided approximately twice the embedment strength of OSB at 5% offset yield. Although still apparent, the margin between the two was significantly less at capacity. Note also that the COVs associated with OSB embedment strength are generally higher than those associated with plywood embedment strengths.

Table 4.19: Average embedment strengths and associated COVs of OSB and plywood (values in pounds per square inch).

			$^{7}/_{16}$" OSB	$^{3}/_{8}$" Plywood	$^{23}/_{32}$" OSB	$^{3}/_{4}$" Plywood
5% Offset Yield	8d Common Nail	Average	3947	7672		
		COV	22.2%	19.8%		
	10d Common Nail	Average	3295	6421	4142	8381
		COV	39.5%	25.5%	20.7%	9.2%
	16d Common Nail	Average			3656	8283
		COV			16.9%	8.1%
Capacity	8d Common Nail	Average	5863	9780		
		COV	12.2%	18.0%		
	10d Common Nail	Average	5146	8843	7616	11536
		COV	20.1%	11.5%	14.1%	8.5%
	16d Common Nail	Average			6751	10942
		COV			13.7%	9.2%

4.4.2 – Nail Embedment Tests on Solid Wood Members

All embedment tests on solid wood members of nailed connections were conducted using the half-hole test method. Thorough descriptions of specimen preparation and testing procedures are provided in Sections 3.3.3 and 3.6.2, respectively. Controlled test variables were nail diameter (0.099”, 0.120”, 0.131”, 0.148”, and 0.162”) and commercial species group (SPF and Southern Pine). As was stated in Section 3.3, moisture content variability was minimized through conditioning. This also ensured that embedment specimens would have moisture contents nearly identical to those of their corresponding connection members. Specific gravity was not a controlled test variable. Results of specific gravity and moisture content tests are presented in Section 4.6.

Load-deflection behavior of nail embedment in solid wood was characterized by relatively high variability (as compared to those of embedment results for panel products). Trends in average resistance were, however, apparent with respect to both nail diameter and species group. Embedment strengths typically decreased with respect to nail diameter. This is explained by the fact that larger nail diameters had a greater tendency to split the wood when driven. In terms of species group, nail embedment strengths were generally greater in Southern Pine. This trend was expected, as Southern Pine specimens had greater average specific gravity. Embedment strength averages at 5% offset yield and capacity for the various nail diameters and species groups are given with corresponding COVs in Table 4.20.

Table 4.20: Average nail embedment strengths and associated COVs for solid wood members (values in pounds per square inch).

			Nail Diameter				
			0.099"	0.120"	0.131"	0.148"	0.162"
5% Offset Yield	SPF	Average			3212	3747	3953
		COV			17.4%	20.6%	24.9%
	SYP	Average	5253	4290	4411		4453
		COV	26.9%	24.3%	24.1%		35.0%
Capacity	SPF	Average			3630	4391	4582
		COV			19.5%	19.4%	23.5%
	SYP	Average	6154	4963	4900		4942
		COV	22.9%	22.1%	22.1%		32.3%

4.4.3 – Bolt Embedment Tests

Embedment tests corresponding to members of bolted connections followed the half-hole testing method. Tests involving a bolt diameter of $^3/_8$” were conducted using a bolt simulator while tests involving ½" and $^5/_8$" bolt diameters were conducted using actual bolts. Detailed descriptions of bolt embedment specimen fabrication and testing methods are provided in Sections 3.3.3 and 3.6.2. Controlled test variables were: 1) bolt diameter, 2) bearing length (1.5", 3.0", or 3.5", depending upon cross-sectional dimensions of corresponding connection member), and 3) commercial species group (SPF or Mixed Southern Pine). As with solid wood *nail* embedment tests, specific gravity was not a controlled variable. Moisture content variability was limited through conditioning.

While average total resistance loads tended to increase with respect to bolt diameter, embedment strengths decreased. Mixed Southern Pine 2x4 and Spruce-Pine-Fir 2x4 specimens usually had about the same embedment strengths. Of 4x4 (and simulated 4x4) specimens, however, Southern Pine members had greater average embedment strengths than those of SPF. This is explained by the fact that Southern Pine 4x4 material had a higher average specific gravity than SPF simulated 4x4 material. Variability of resistance values observed in bolt embedment tests was generally lower than that of resistance values observed in solid wood nail embedment tests. As was observed in nail embedment tests, variability was greater in Southern Pine specimens than SPF specimens. Average embedment strengths, as well as corresponding COVs, for the main and side members of the twelve bolted connection sets are provided in Table 4.21.

Table 4.21: Average embedment strengths and associated COVs of bolted connection members (values in pounds per square inch).

			SPF 2x4	SPF 4x4	SYP 2x4	SYP 4x4
5% Offset Yield	$^3/_8$" Bolt	Average	4939	4348	4809	5245
		COV	17.7%	13.8%	26.9%	15.5%
	$^1/_2$" Bolt	Average	4196	3428	4163	4617
		COV	15.7%	13.4%	20.1%	17.4%
	$^5/_8$" Bolt	Average	3547	3341	3979	4311
		COV	12.3%	11.8%	16.1%	14.6%
Capacity	$^3/_8$" Bolt	Average	5167	4639	5053	5419
		COV	17.3%	12.4%	26.8%	15.2%
	$^1/_2$" Bolt	Average	4237	3524	4230	4776
		COV	14.9%	13.3%	19.5%	17.0%
	$^5/_8$" Bolt	Average	3605	3419	4005	4349
		COV	12.0%	11.2%	15.7%	14.4%

Table 4.22: Average plastic moments and bending strengths (and associated COVs) of nails and bolts.

			5% Offset Yield		Ultimate		NDS Default Value for Bending Yield Strength (psi)
			Bending Yield Moment (in-lbs)	Bending Yield Strength (psi)	Bending Moment (in-lbs)	Bending Strength (psi)	
Nails	1 3/8" Drywall	Average:	19.4	111,020	24.6	140,647	
		COV:	4.4%	3.9%	3.3%	3.4%	
	1 1/2" Roof	Average:	31.2	106,014	43.5	147,677	
		COV:	8.7%	7.2%	4.7%	3.2%	
	6d Box	Average:	17.7	107,692	22.3	135,656	100,000
		COV:	2.7%	2.6%	2.2%	2.3%	
	8d Common	Average:	42.5	102,177	51.9	124,876	100,000
		COV:	10.9%	11.3%	6.3%	6.6%	
	10d Common	Average:	54.4	100,618	67.1	124,197	90,000
		COV:	2.5%	2.8%	1.8%	2.1%	
	16d Common	Average:	62.6	81,809	78.5	102,622	90,000
		COV:	6.7%	6.8%	1.6%	1.9%	
Bolts	f = 3/8"	Average:	749	89,079	878	104,391	45,000
		COV:	1.3%	1.1%	5.2%	5.3%	
	f = 1/2"	Average:	1,817	90,646	2,100	104,756	45,000
		COV:	1.0%	1.1%	0.4%	0.6%	
	f = 5/8"	Average:	5,863	147,664	7,005	176,446	45,000
		COV:	4.0%	4.0%	3.1%	3.1%	

4.5 – Fastener (Dowel) Bending Tests

Load and deflection data recorded from dowel bending tests were analyzed using the same program as was used for connection and embedment test data. After analysis, 5% offset yield and capacity resistances were used to calculate fastener plastic moments, M_p, as well as bending yield strengths, F_{yb}. These values were calculated at both 5% offset yield and capacity and used as inputs for calculation of theoretical connection resistance at both 5% offset yield and capacity, respectively. The average plastic moment of *ten* specimens for each fastener type was obtained and used in yield model calculations. For nails, bending moments at 5% offset yield represented between 70% and 80% of the bending moments at capacity. For bolts, this same ratio was between 80% and 90%. Average bending moments and corresponding maximum bending stresses within each of the nine dowel types are given, along with corresponding COVs in Table 4.22. As is evident by the data presented in this table, variability was relatively low in all cases except for that of 8d common nails and $^{3}/_{8}$" diameter bolts. One of the ten $^{3}/_{8}$" diameter bolts tested had significantly higher strength properties than the other nine. This greatly increased both the average plastic moment and its associated COV. The average plastic moment without the values of this single bolt would have been 749 in-lb at 5% offset yield and 863 in-lb at capacity, whereas average values including data from this bolt are 765 in-lb and 878 in-lb, respectively. Corresponding COVs increased from 1.32% at 5% offset yield and 0.87% at capacity to 6.44% and 5.20%, respectively.

4.6 – Moisture Contents and Specific Gravities

Moisture contents and specific gravities were measured for both the main and side member of every connection specimen. These measurements were obtained following testing procedures described in Section 3.6.4. The average moisture contents of SPF connection members was 13.2% with a COV of 9.83%. Moisture contents of Mixed Southern Pine members averaged 13.5% with a COV of 11.8%. Southern Pine members had an average moisture content of 14.7% with a COV of 8.42%. Average *specific gravities* for connection members from these three commercial species groups were 0.435, 0.493 and 0.518, respectively, with corresponding COVs of 15.3%, 12.7% and 14.7%. COVs corresponding to *within* set average moisture content and specific gravity measurements for solid wood members were lower than the aforementioned values.

Panel product moisture contents and specific gravities fluctuated greatly between material types, but had relatively low variability within each set. Averages and COVs for specific gravity and moisture content are presented for side members of panel-type connections in Tables 4.23 through 4.26. Each value in these tables represent the average specific gravity, moisture content, or the associated COV of the side members of connections having the same side member type and thickness. Measurements for individual connection members (both main and side) are given in Appendix C.

Table 4.23: Average moisture contents and specific gravities of gypsum wallboard side members.

		Mill E	Mill F	Mill G
Specific Gravity	Average	0.510	0.553	0.540
	COV	4.2%	4.3%	3.5%
Moisture Content	Average	16.6%	16.8%	17.1%
	COV	10.2%	12.3%	9.9%

Table 4.24: Average moisture contents and specific gravities of fiberboard side members.

		Mill A	Mill B	Mill C	Mill D
Specific Gravity	Average	0.320	0.361	0.326	0.321
	COV	4.4%	1.3%	1.6%	3.0%
Moisture Content	Average	9.3%	7.1%	9.3%	8.8%
	COV	5.1%	4.6%	6.3%	3.8%

Table 4.25: Average moisture contents and specific gravities of hardboard side members.

		Mill H	Mill I	Mill J
Specific Gravity	Average	0.746	0.836	0.809
	COV	1.8%	2.3%	2.0%
Moisture Content	Average	8.7%	7.9%	8.8%
	COV	3.2%	9.6%	6.1%

Table 4.26: Average moisture contents and specific gravities of plywood and OSB side members.

		$^{7}/_{16}$" OSB	$^{23}/_{32}$" OSB	$^{3}/_{8}$" Plywood	$^{3}/_{4}$" Plywood
Specific Gravity	Average	0.648	0.617	0.581	0.616
	COV	6.6%	4.6%	8.8%	4.6%
Moisture Content	Average	10.7%	11.5%	11.9%	11.8%
	COV	14.0%	4.0%	9.2%	6.7%

4.7 – Evaluation of the Yield Theory

Values were calculated for theoretical resistance using the yield theory at 5% offset yield as well as at capacity. Five-percent offset yield calculations were made using each connection member's embedment strength at 5% offset yield, and average dowel bending moment at 5% offset yield. Calculations of theoretical connection *capacity* were made by substituting each connection member's *ultimate* embedment strength and average *fully*-plastic dowel-bending moment into the same equations. This was done based upon the assumption that yield modes exhibited at a connection's 5% offset yield will also govern its lateral resistance at capacity, before failure (i.e., cracking in the members, fastener pull-out, etc.) is initiated. Average calculated values and associated COVs for each set at both 5% offset yield and capacity are presented in this section. Since the embedment strengths used to calculate theoretical connection resistance were derived from tests lasting ten minutes or less, the load duration factor of 1.6 is not used in the calculation of lateral resistance (i.e., the ten minute load duration factor is already effectively built in). Using calculated values for 5% offset yield, nominal lateral design values were determined for each connection according to procedures outlined in both the NDS® and the LRFD Manual. Theoretical (calculated) values are then compared to actual test results to derive calculated-to-tested ratios (C/T ratios) as well as observed factors of safety. Theoretical resistance values and C/T ratios for each individual connection specimen are given in Appendix C.

4.7.1 – Theoretical Connection Resistance Values

Average theoretical resistance values at both 5% offset yield and capacity are presented along with their associated COVs for each connection set in Tables 4.27 through 4.32. Many of the same trends observed in test results are evident in these calculated values. Values in Table 4.27, for example, indicate significantly higher resistances of gypsum wallboard connections made with material manufactured at Mill E, as was also noted in connection test results. Tables 4.31 and 4.32 also include NDS tabulated lateral 5% offset yield design values multiplied by the ten-minute load duration factor of 1.6 for comparison with calculated values. These NDS tabulated design values are for connections having the same fastener type and diameter as well as the same main and side member thickness and species. It must be noted that these tabulated design values are different from the theoretical values in that they represent a theoretical resistance value, P_{min}, divided by the terms n and K, as shown in Equation 2.8 and discussed in Section 2.3.1. Since the NDS does not have tabulated lateral resistance values for connections with gypsum wallboard, fiberboard, hardboard, OSB and plywood, Tables 4.27 through 4.30 do not contain these values.

Table 4.27: Theoretical (calculated) lateral resistance values at 5% offset yield and capacity for gypsum wallboard connections.

			Mill E	Mill F	Mill G
5% Offset Yield	$1^3/_8$" Drywall Nail	Average	43	33	30
		COV	10.8%	13.1%	5.4%
	Roofing Nail	Average	46	35	33
		COV	8.9%	11.5%	7.9%
Capacity	$1^3/_8$" Drywall Nail	Average	79	67	62
		COV	3.5%	7.7%	4.6%
	Roofing Nail	Average	89	71	67
		COV	7.7%	9.5%	6.6%

Table 4.28: Theoretical (calculated) lateral resistance values at 5% offset yield and capacity for fiberboard connections.

			Mill A	Mill B	Mill C	Mill D
5% Offset Yield	6d Box Nail	Average	36	44	38	53
		COV	9.3%	10.7%	24.8%	13.7%
	8d Common Nail	Average	38	50	38	58
		COV	29.9%	18.6%	6.8%	17.2%
Capacity	6d Box Nail	Average	71	78	70	79
		COV	4.7%	4.0%	5.4%	6.1%
	8d Common Nail	Average	85	92	80	103
		COV	24.2%	8.5%	7.7%	8.0%

Table 4.29: Theoretical (calculated) lateral resistance values at 5% offset yield and capacity for hardboard connections.

			Mill H	Mill I	Mill J
5% Offset Yield	6d Box Nail	Average	97	93	114
		COV	9.8%	7.2%	11.1%
	8d Common Nail	Average	159	156	163
		COV	10.0%	9.7%	8.4%
Capacity	6d Box Nail	Average	145	144	175
		COV	4.3%	7.9%	9.2%
	8d Common Nail	Average	204	193	218
		COV	4.2%	5.8%	6.1%

Table 4.30: Theoretical (calculated) lateral resistance values at 5% offset yield and capacity for OSB and plywood connections.

			Side Member Material			
			$^{7}/_{16}$" OSB	$^{3}/_{8}$" Plywood	$^{23}/_{32}$" OSB	$^{3}/_{4}$" Plywood
5% Offset Yield	8d Common Nail	Average	149	162		
		COV	8.8%	8.7%		
	10d Common Nail	Average	167	201	216	282
		COV	13.4%	10.8%	11.2%	7.5%
	16d Common Nail	Average			225	316
		COV			12.1%	6.9%
Capacity	8d Common Nail	Average	192	195		
		COV	5.9%	9.6%		
	10d Common Nail	Average	222	257	322	348
		COV	8.4%	5.2%	6.6%	6.6%
	16d Common Nail	Average			344	395
		COV			11.0%	8.8%

Table 4.31: Theoretical (calculated) lateral resistance values at 5% offset yield and capacity for solid wood, nailed connections. NDS tabulated lateral resistance values, adjusted by the ten-minute load duration factor of 1.6, are also included.

		SPF	SYP
5% Offset Yield	Average	280	280
	COV	7.7%	17.2%
	Tabulated	192	246
Capacity	Average	333	339
	COV	8.9%	10.9%

Table 4.32: Theoretical (calculated) lateral resistance values at 5% offset yield and capacity for OSB and plywood connections. NDS tabulated lateral resistance values, adjusted by the ten-minute load duration factor of 1.6, are also included. Tabulated design values for connections with 3/8" bolts are not given in the NDS.

			Main Member Material			
			SPF 2x4	SPF 4x4	SYP 2x4	SYP 4x4
5% Offset Yield	3/8" Bolt	Average	1233	1211	1235	1296
		COV	7.4%	6.6%	16.5%	6.0%
		Tabulated				
	1/2" Bolt	Average	1368	1732	1377	1955
		COV	6.4%	8.3%	8.9%	8.3%
		Tabulated	656	864	848	1056
	5/8" Bolt	Average	1345	2220	1585	2754
		COV	8.9%	10.6%	9.8%	16.2%
		Tabulated	816	1248	1056	1504
Capacity	3/8" Bolt	Average	1285	1329	1297	1395
		COV	8.0%	5.3%	16.3%	5.6%
	1/2" Bolt	Average	1374	1799	1396	2067
		COV	6.7%	8.7%	8.6%	9.5%
	5/8" Bolt	Average	1371	2250	1596	2773
		COV	9.1%	9.4%	9.7%	15.7%

The relationships between predicted resistances at capacity and 5% offset yield are shown in Figures 4.26 and 4.27 for nailed and bolted connections, respectively. Least squares regressions fitted to this data indicate strong correlations, with R-squared values of 0.929 for nailed connections and 0.987 for bolted connections. The R-squared value associated with the linear regression fit to nailed connection data is reduced due to the fact that gypsum wallboard and fiberboard connections had relatively high ratios of resistance at capacity to resistance at 5% offset yield. This, in turn, was brought about by the fact that these connections (and their corresponding embedment specimens) underwent bearing compaction at higher deflections. Note that the slopes of these relationships are not as great as those found for actual test results; shown in Figures 4.15 and 4.25 of Sections 4.2.6 and 4.3.1, respectively. This is due to the fact that the yield theory does not account for certain factors, such as friction, tension in the dowel, and fastener withdrawal, which affect connection resistance at higher deflections.

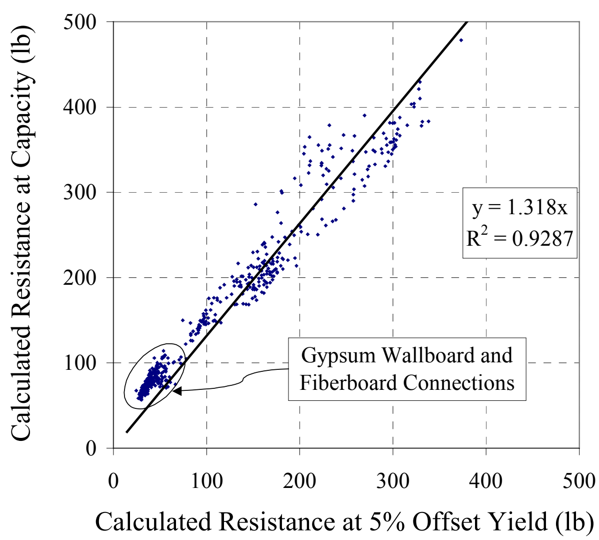

Figure 4.26: Calculated resistances at capacity vs. those at 5% offset yield for all nailed connections.

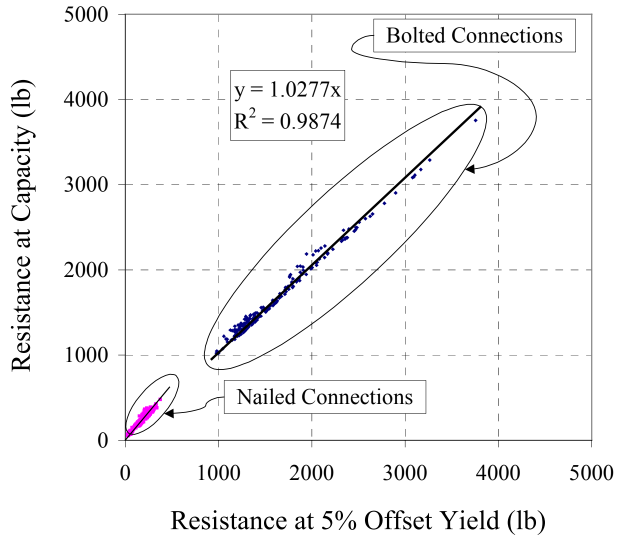

Figure 4.27: Calculated resistances at capacity vs. those at 5% offset yield for all bolted connections.

4.7.2 – Comparison of Calculated Values to Test Values

Relationships between calculated values and test results are expressed in the form of C/T ratios, as previously described in section 4.7. Statistical comparisons of mean calculated resistances to mean test results were conducted for each connection set in an effort to quantify the significance of their differences. Tables 4.33 through 4.37 contain average C/T ratios and associated COVs for each nailed connection set. Also contained in these tables are the probabilities (p-values) associated with two-tailed, paired T-tests. The null hypothesis of these tests is that there is no significant difference between mean calculated resistance and mean observed (tested) resistance. Values shown in bold print within these tables denote the p-values of T-tests that failed to detect a significant difference in means at, or above, the commonly used alpha level of 0.05 or greater. In order to further distinguish these values, the cells in which they are given are shaded.

4.7.2.1 – Comparison of Calculated Values to Test Values (Nailed Connections)

Average C/T ratios for nailed connections ranged from 0.55 to 1.0. The lower end of this spectrum is comprised predominantly of values corresponding to hardboard connections. This is most likely do to the fact that the half-hole embedment tests conducted on hardboard tended to crush the material to a greater extent than was observed in the actual connections, thereby resulting in low apparent embedment strengths. As was discussed in Section 3.3.3, the half-hole test method was necessary to prevent bending in the nail. Had full hole embedment tests been possible in hardboard, C/T ratios would have most likely been comparable to those of nailed connections having other panel-type materials (such as OSB or plywood), which ranged from 0.83 to 0.95.

Table 4.33: Average C/T ratios, associated COVs, and p-values of T-tests comparing mean calculated to mean tested values for gypsum wallboard connections.

			Mill E	Mill F	Mill G
5% Offset Yield	$1^3/_8$" Drywall Nail	Average	0.821	0.717	0.687
		COV	14.1%	18.4%	11.2%
		p-value	0.000	0.000	0.000
	Roofing Nail	Average	0.702	0.646	0.569
		COV	14.8%	14.6%	10.7%
		p-value	0.000	0.000	0.000
Capacity	$1^3/_8$" Drywall Nail	Average	0.767	0.782	0.770
		COV	4.9%	7.8%	8.2%
		p-value	0.000	0.000	0.000
	Roofing Nail	Average	0.753	0.826	0.809
		COV	9.6%	14.2%	9.3%
		p-value	0.000	0.000	0.000

Table 4.34: Average C/T ratios, associated COVs, and p-values of T-tests comparing mean calculated to mean tested values for fiberboard connections. Shaded cells and bolded font denote p-values of T-tests where the difference between means was insignificant.

			Mill A	Mill B	Mill C	Mill D
5% Offset Yield	6d Box Nail	Average	1.095	1.278	1.081	1.192
		COV	11.4%	17.5%	24.8%	18.1%
		p-value	0.011	0.000	**0.283**	0.005
	8d Common Nail	Average	0.823	1.002	0.946	0.961
		COV	29.1%	22.2%	13.1%	16.4%
		p-value	0.022	**0.890**	**0.079**	**0.279**
Capacity	6d Box Nail	Average	0.902	0.967	0.889	0.832
		COV	9.7%	4.7%	10.9%	12.3%
		p-value	0.001	0.008	0.001	0.000
	8d Common Nail	Average	0.917	0.847	0.819	1.007
		COV	21.6%	9.5%	12.3%	11.1%
		p-value	**0.166**	0.000	0.000	**0.945**

Table 4.35: Average C/T ratios, associated COVs, and p-values of T-tests comparing mean calculated to mean tested values for hardboard connections. Shaded cells and bolded font denote p-values of T-tests where the difference between means was insignificant.

			Mill H	Mill I	Mill J
5% Offset Yield	6d Box Nail	Average	0.974	0.799	0.977
		COV	11.6%	11.7%	13.6%
		p-value	**0.320**	0.000	**0.252**
	8d Common Nail	Average	0.904	0.930	0.865
		COV	9.9%	9.2%	12.6%
		p-value	0.000	0.004	0.000
Capacity	6d Box Nail	Average	0.693	0.612	0.706
		COV	9.8%	11.4%	14.6%
		p-value	0.000	0.000	0.000
	8d Common Nail	Average	0.553	0.600	0.557
		COV	7.8%	9.5%	12.8%
		p-value	0.000	0.000	0.000

Table 4.36: Average C/T ratios, associated COVs, and p-values of T-tests comparing mean calculated to mean tested values for OSB and Plywood connections. Shaded cells and bolded font denote p-values of T-tests where the difference between means was insignificant.

			Side Member Material			
			7/16" OSB	3/8" Plywood	23/32" OSB	3/4" Plywood
5% Offset Yield	8d Common Nail	Average	1.242	1.397		
		COV	21.0%	8.3%		
		p-value	0.004	0.000		
	10d Common Nail	Average	1.093	1.318	1.213	1.413
		COV	25.1%	12.6%	21.9%	11.9%
		p-value	**0.502**	0.000	0.009	0.000
	16d Common Nail	Average			1.055	1.427
		COV			18.4%	13.8%
		p-value			**0.381**	0.000
Capacity	8d Common Nail	Average	0.943	0.945		
		COV	15.6%	10.0%		
		p-value	**0.099**	0.048		
	10d Common Nail	Average	0.831	0.881	0.911	0.906
		COV	12.9%	20.3%	20.7%	15.7%
		p-value	0.000	0.021	**0.071**	0.019
	16d Common Nail	Average			0.890	0.935
		COV			25.8%	19.5%
		p-value			0.044	**0.115**

Table 4.37: Average C/T ratios, associated COVs, and p-values of T-tests comparing mean calculated to mean tested values for solid wood, nailed connections.

		SPF	SYP
5% Offset Yield	Average	1.375	1.340
	COV	13.1%	23.4%
	p-value	0.000	0.001
Capacity	Average	0.828	0.902
	COV	19.3%	14.8%
	p-value	0.003	0.010

When evaluated at 5% offset yield, average C/T ratios for nailed connections appear to decrease with respect to nail diameter. At capacity, the same trend is evident only for configurations exhibiting Mode III_s yield. No significant difference was detected between mean C/T ratios at varying nail diameters for connections yielding by Modes I_s (gypsum wallboard and fiberboard connections) or IV (23/32" OSB and ¾" plywood connections) at capacity. T-tests were conducted for comparison of mean C/T ratios with respect to nail diameter assuming unequal variances. Probability-values associated with these T-tests are given in Tables 4.38 and 4.39. It should additionally be noted from Table 4.39 that C/T ratios evaluated at capacity are not subject to the same fluctuations with respect to side member material type as those evaluated at 5% offset yield. The higher C/T ratios at 5% offset yield for *plywood* connections (as compared to those for OSB connections) are reflected in the fact that their corresponding embedment strengths were higher, while connection test results were approximately the same for both OSB and plywood connections. With corresponding p-values of 0.720 and 0.221, t-tests revealed no significant difference between the C/T ratios of solid wood nailed connection sets at either 5% offset yield or capacity, respectively. This is most likely due to the fact that these two connection sets were similar in every way with the exception of their commercial species group. Probability-values from comparison of mean C/T ratios for the two sets of solid wood nailed connections are not given in a table.

Table 4.38: P-values associated with T-tests for comparison of mean C/T ratios with respect to nail diameter in gypsum wallboard, fiberboard, and hardboard connections. Shaded cells and bolded font denote p-values of T-tests where the difference between means was insignificant.

		Side Member Material and Nail Diameter					
		Gypsum Wallboard		Fiberboard		Hardboard	
		ϕ = 0.099"	ϕ = 0.120"	ϕ = 0.099"	ϕ = 0.131"	ϕ = 0.099"	ϕ = 0.131"
5% Offset Yield	C/T	0.743	0.641	1.167	0.935	0.919	0.900
	COV	16.7%	16.0%	19.2%	20.8%	15.2%	10.7%
	p-value	0.000		0.000		**0.435**	
Capacity	C/T	0.774	0.796	0.899	0.898	0.672	0.569
	COV	7.0%	11.9%	10.8%	16.3%	13.6%	10.6%
	p-value	**0.171**		**0.959**		0.000	

Table 4.39: P-values associated with T-tests for comparison of mean C/T ratios with respect to nail diameter in OSB and plywood connections. Shaded cells and bolded font denote p-values of T-tests where the difference between means was insignificant.

		Side Member Material and Nail Diameter							
		7/16" OSB		3/8" Plywood		23/32" OSB		3/4" Plywood	
		ϕ = 0.131"	ϕ = 0.148"	ϕ = 0.131"	ϕ = 0.148"	ϕ = 0.148"	ϕ = 0.162"	ϕ = 0.148"	ϕ = 0.162"
5% Offset Yield	C/T	1.242	1.093	1.397	1.318	1.213	1.055	1.413	1.427
	COV	21.0%	25.1%	8.3%	12.6%	21.9%	18.4%	11.9%	13.8%
	p-value	**0.140**		**0.152**		**0.076**		**0.834**	
Capacity	C/T	0.943	0.831	0.945	0.881	0.911	0.890	0.906	0.935
	COV	15.6%	12.9%	10.0%	20.3%	20.7%	25.8%	15.7%	19.5%
	p-value	0.024		**0.247**		**0.794**		**0.638**	

4.7.2.2 – Comparison of Calculated Values to Test Values (Bolted Connections)

Calculated-to-tested ratios for bolted connections vary depending upon bolt diameter, commercial species grouping, and main member geometry. Average C/T ratios and associated COVs for each set are given in Table 4.40. Just as in Tables 4.33 through 4.37, p-values in this table represent probabilities associated with paired T-tests in which mean theoretical values were compared to mean test results. Note that the only connections in which a significant difference is not detectable at an alpha level of 0.05 are those having 5/8” diameter bolts and simulated SPF 4x4 main members. This is the case only at 5% offset yield, where the average C/T ratio is 0.986. At 5% offset yield, all bolted connections having 3/8” diameter bolts and/or 4x4 main members have C/T ratios of greater than 1.0. This means that calculations made using the Yield Theory over-estimated the resistance provided by these connections. At capacity, resistances for all of the bolted connection sets were significantly underestimated (i.e., having average C/T ratios of less than 1.0).

Table 4.40: Average C/T ratios, associated COVs, and p-values of T-tests comparing mean calculated to mean tested values for bolted connections.

			Main Member Material			
			SPF 2x4	SPF 4x4	SYP 2x4	SYP 4x4
5% Offset Yield	$^3/_8$" Bolt	Average	1.242	1.180	1.123	1.124
		COV	8.4%	12.8%	7.7%	11.0%
		p-value	0.000	0.000	0.000	0.001
	$^1/_2$" Bolt	Average	0.909	1.064	0.828	1.153
		COV	8.0%	10.0%	6.7%	9.7%
		p-value	0.001	0.026	0.000	0.000
	$^5/_8$" Bolt	Average	0.743	0.986	0.650	1.181
		COV	7.6%	7.6%	6.7%	9.5%
		p-value	0.000	**0.387**	0.000	0.000
Capacity	$^3/_8$" Bolt	Average	0.672	0.794	0.590	0.693
		COV	9.4%	7.2%	5.5%	8.3%
		p-value	0.000	0.000	0.000	0.000
	$^1/_2$" Bolt	Average	0.525	0.705	0.450	0.720
		COV	14.0%	8.5%	11.3%	8.0%
		p-value	0.000	0.000	0.000	0.000
	$^5/_8$" Bolt	Average	0.440	0.620	0.365	0.746
		COV	9.4%	10.4%	8.3%	10.6%
		p-value	0.000	0.000	0.000	0.000

Relationships between C/T ratios, bolt diameter, and main member material type are shown graphically at 5% offset yield in Figure 4.28 and at capacity in Figure 4.29. Note that C/T ratios of configurations having 2x4 main members decrease with respect to bolt diameter in all cases, while the same is not necessarily true of those having 4x4 main members. The significance of these differences are quantified by p-values given in Tables 4.41 and 4.42. The lowest C/T ratios were observed in connections where the greatest rigid bolt rotation was possible. Thus, low C/T ratios were observed in connection configurations having thin (2x4) main members and bolt diameters sufficiently large so as to prevent the formation of a plastic hinge. This is due to the fact that theoretically-calculated values do not account for either friction or tension within the rotated bolt; both of which account for a greater percentage of the total connection resistance within these configurations than in others. Note that the order of main member material types in these graphs is different than that in which they are presented in Table 4.40. Main member material types were arranged in this manner to make the bar graphs easier to read.

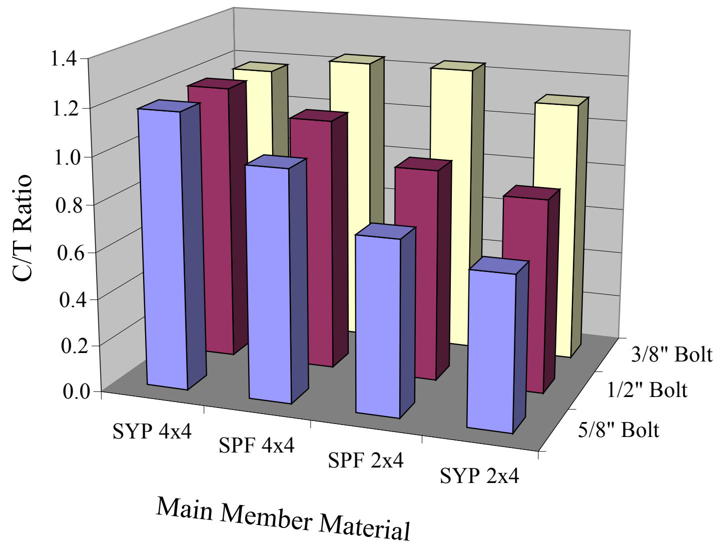

Figure 4.28: C/T ratios of bolted connections (evaluated at 5% offset yield).

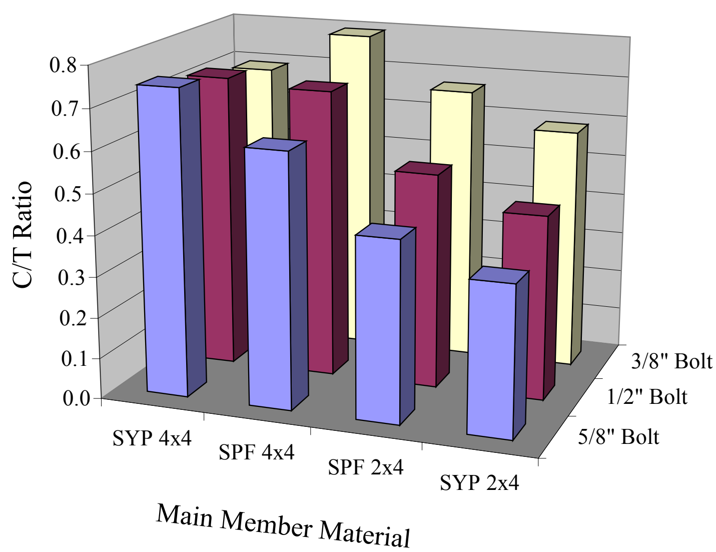

Figure 4.29: C/T ratios of bolted connections (evaluated at capacity).

Table 4.41: P-values associated with T-tests for comparison of mean C/T ratios with respect to bolt diameter in bolted connections having 4x4 main members. Shaded cells and bolded font denote p-values of T-tests where the difference between means was insignificant.

		Main Member Material					
		SYP 4x4			SPF 4x4		
		3/8" Bolt	1/2" Bolt	5/8" Bolt	3/8" Bolt	1/2" Bolt	5/8" Bolt
5% Offset Yield	C/T	1.124	1.153	1.181	1.180	1.064	0.986
	COV	11.0%	9.7%	9.5%	12.8%	10.0%	7.6%
	p-value (3/8" vs 1/2"; 1/2" vs 5/8")	**0.491**		**0.465**	0.018		0.020
	p-value (3/8" vs 5/8")	**0.172**			0.000		
Capacity	C/T	0.693	0.720	0.746	0.794	0.705	0.620
	COV	8.3%	8.0%	10.6%	7.2%	8.5%	10.4%
	p-value (3/8" vs 1/2"; 1/2" vs 5/8")	**0.186**		**0.282**	0.000		0.000
	p-value (3/8" vs 5/8")	0.034			0.000		

Table 4.42: P-values associated with T-tests for comparison of mean C/T ratios with respect to bolt diameter in bolted connections having 2x4 main members.

		Main Member Material					
		SYP 2x4			SPF 2x4		
		3/8" Bolt	1/2" Bolt	5/8" Bolt	3/8" Bolt	1/2" Bolt	5/8" Bolt
5% Offset Yield	C/T	1.123	0.828	0.650	1.242	0.909	0.743
	COV	7.7%	6.7%	6.7%	8.4%	8.0%	7.6%
	p-value (3/8" vs 1/2"; 1/2" vs 5/8")	0.000		0.000	0.000		0.000
	p-value (3/8" vs 5/8")	0.000			0.000		
Capacity	C/T	0.590	0.450	0.365	0.672	0.525	0.440
	COV	5.5%	11.3%	8.3%	9.4%	14.0%	9.4%
	p-value (3/8" vs 1/2"; 1/2" vs 5/8")	0.000		0.000	0.000		0.001
	p-value (3/8" vs 5/8")	0.000			0.000		

Although increases in actual connection resistance due to friction and tension transferred through the lateral component of the (rotated) bolt are more apparent in connections exhibiting yield Mode II, these same phenomena also serve to increase resistance provided by other bolted connections. This is especially the case at capacity, where the increased test values resulted in C/T ratios of lower than 0.800 for all sets. Logically, friction between the two members and tension within the bolt increase with respect to connection slip (displacement). This is because bolt rotation is increased while end fixity (brought about by the bolt head, nut, and washers) prevents dowel withdrawal, thereby resulting in bolt tensioning and an increase in normal force between the two members. An example of the relationship between C/T ratios evaluated at varying connection slips, δ, is illustrated in Figure 4.30. This graph shows data from the bolted connection set having $^3/_8$" bolts and 2x4 SPF main members (set 03-11). With the exception of the C/T ratio given at 5% offset yield in the text box, these ratios (shown as red dots on the graph) are calculated at finite connection slips as follows:

$$(C/T)_\delta = \frac{\sum_{i=1}^{n}\left(\frac{C_{ult,i}}{T_{\delta,i}}\right)}{n} \tag{4.3}$$

Where $C_{ult,i}$ is the calculated theoretical capacity resistance of the i^{th} connection in the set, $T_{\delta,i}$ is the actual (tested) resistance of the i^{th} connection at a slip of δ, and n is the number of connections in the set. In other words, these values represent average C/T ratios evaluated using theoretical resistance at capacity, and compared to test results for connection resistance at finite connection slip increments. Note that this relationship is asymptotic in nature. The asymptote for each set, shown as a dotted line in Figure 4.30 for set 03-11, is assumed to be the C/T ratio where both calculated and tested resistance are evaluated at connection capacity. In certain cases at higher connection slips, there is an average C/T ratio which is lower than the average C/T ratio at capacity. This occurs because said data points represent a reduced sample size due to the fact that other connections failed prior to that point. The average *capacity* C/T ratio, on the other hand, is calculated using capacity resistance of each connection within the set, regardless of connection slip. Range bars on data points represent the total range of

C/T ratios at the given connection slip. Values along the x-axes of these charts represent connection slip beyond the slack point. This was done to eliminate the variable of slack, which varied both within and between sets.

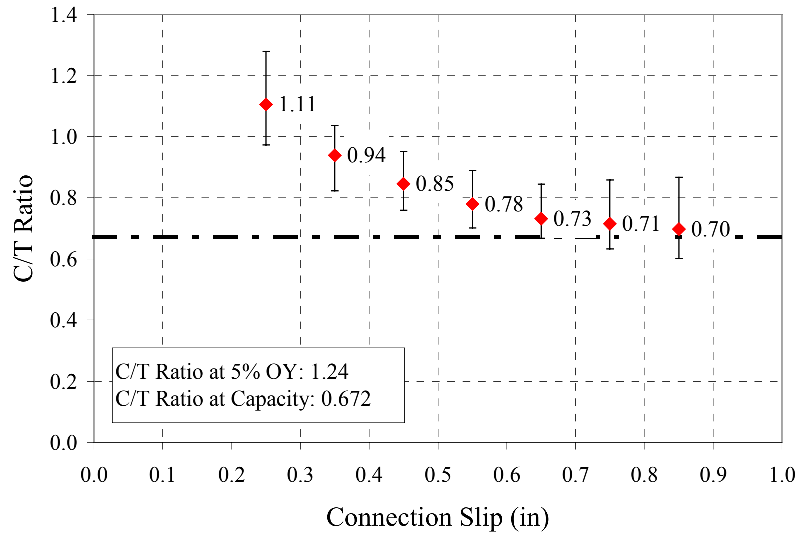

Figure 4.30: Example of C/T ratios, based upon calculated resistance at capacity, evaluated with test resistances at various connection slips (connection set 03-11).

4.7.3 – Observed Over-Strengths

Factors of safety and over-strengths were calculated by computing the ratio of observed (actual) connection resistance at capacity to lateral design values specified by the NDS® and LRFD Manuals, respectively. Although they are both arrived at through the division of capacity resistance by the Z-values discussed in Chapter 2, they are referred to differently in this thesis. This is because of the different values they represent in their respective design procedures. As discussed in Chapter 2, the Z-value in Equation 2.8 is a *nominal design value*, whereas the same variable in Equation 2.29 is termed *reference lateral resistance*. The main difference between the two values is that the nominal design value is an allowable stress, whereas the reference lateral resistance must be modified by a resistance factor of 0.65 and expected loads must be factored. This difference reflects the fact that the reference lateral resistance is supposed to represent connection capacity. Thus, the ratio of actual capacity resistance to reference lateral resistance (denoted as $^{Cap}/_{LRFD\ Z}$ in the following tables) is referred to as over-strength while the ratio of actual capacity resistance to nominal design value (denoted as $^{Cap}/_{NDS\ Z}$ in the following tables) is referred to as a factor of safety. Due to the fact that connection test results were typically obtained within a ten minute period, nominal design values were calculated using a load duration factor, C_D, of 1.6, as specified by the NDS®. Reference lateral resistances were not modified, as the maximum permissible time effect factor, λ, for connections is 1.0 (also based upon a 10 minute load duration). Note that the ratio between the factor of safety and over-strength is constant at approximately 2.1 due to the way in which each Z-value is calculated (see Sections 2.3.1 and 2.3.3). For this reason, the COV associated with the average observed factor of safety is the same as that associated with the average over-strength. All three of these values (i.e., factor of safety, over-strength, and associated COV) are presented with respect to both connection configuration as well as yield mode in this section.

Observed over-strengths in connections having gypsum wallboard, fiberboard, and hardboard side members were typically over 1.5. Fluctuations were apparent, however, with respect to all test variables, including material type, side member manufacturer, and, in the case of fiberboard connections, nail diameter. Gypsum wallboard connections had the highest average over-strengths. This is due to increases in observed strength due to bearing compaction. The 5% offset yield embedment strengths used in design calculations are derived at a point prior to the onset of this phenomenon, and thus do not account for it. Fiberboard connections with 6d box nails (ϕ = 0.099") typically had lower over-strengths than those with 8d common nails (ϕ = 0.131"). This can be explained by the fact that connections with smaller diameter nails often underwent a mode shift (I_s to III_s) between 5% offset yield and capacity, as described in Sections 4.2.1 and 4.2.2. Development of a plastic hinge within the nail thereby limited any increases in resistance, brought about by bearing compaction, which would otherwise be observed under Mode I_s conditions. Observed factors of safety, over-strengths, and associated COVs for gypsum wallboard, fiberboard, and hardboard connections are presented in Tables 4.43, 4.44, and 4.45, respectively.

Table 4.43: Observed factors of safety, over-strengths, and associated COVs for gypsum wallboard connections.

		Mill E	Mill F	Mill G
$1^3/_8$" Drywall Nail	$^{Cap}/_{NDS\ Z}$	3.39	3.64	3.68
	$^{Cap}/_{LRFD\ Z}$	1.64	1.76	1.78
	COV	10.7%	6.7%	9.0%
Roofing Nail	$^{Cap}/_{NDS\ Z}$	3.61	3.45	3.40
	$^{Cap}/_{LRFD\ Z}$	1.75	1.67	1.65
	COV	9.8%	11.6%	8.7%

Table 4.44: Observed factors of safety, over-strengths, and associated COVs for fiberboard connections.

		Mill A	Mill B	Mill C	Mill D
6d Box Nail	$^{Cap}/_{NDS\ Z}$	3.05	2.56	2.99	2.53
	$^{Cap}/_{LRFD\ Z}$	1.48	1.24	1.45	1.22
	COV	13.7%	11.1%	20.7%	19.9%
8d Common Nail	$^{Cap}/_{NDS\ Z}$	3.49	3.07	3.59	2.51
	$^{Cap}/_{LRFD\ Z}$	1.69	1.49	1.74	1.22
	COV	20.9%	19.2%	11.8%	14.6%

Table 4.45: Observed factors of safety, over-strengths, and associated COVs for hardboard connections.

		Mill H	Mill I	Mill J
6d Box Nail	$^{Cap}/_{NDS\ Z}$	3.01	3.52	3.06
	$^{Cap}/_{LRFD\ Z}$	1.46	1.71	1.48
	COV	11.7%	10.0%	13.3%
8d Common Nail	$^{Cap}/_{NDS\ Z}$	3.24	2.86	3.34
	$^{Cap}/_{LRFD\ Z}$	1.57	1.39	1.62
	COV	9.1%	10.1%	10.4%

Nailed OSB and plywood connections exhibited lower over-strengths than the other panel-type connections. Over-strengths of these connections are typically around 1.0 (i.e., no appreciable difference between the observed capacity and reference lateral resistance). Differences are not readily apparent with respect to side member thickness, however, OSB connections generally have higher over-strengths than plywood connections. The inverse of this relationship is noted in C/T ratios evaluated at 5% offset yield (Section 4.7.2.1). Over-strengths also tend to increase with respect to nail diameter. Nail connections having solid wood side members are comparable in over-strength to panel-type connections in OSB and plywood. No significant difference is observed between the mean over-strength of SPF connections and that of Southern Pine connections. Mean observed factors of safety, over-strengths, and associated COVs of OSB and plywood connections are presented Table 4.46. The same values for solid wood nailed connections are presented in Table 4.47, in addition to the factors of safety of the NDS tabulated values where the load duration factor of 1.6 is applied.

Table 4.46: Observed factors of safety, over-strengths, and associated COVs for OSB and plywood connections.

		Side Member Material			
		$^{7}/_{16}$" OSB	$^{3}/_{8}$" Plywood	$^{23}/_{32}$" OSB	$^{3}/_{4}$" Plywood
8d Common Nail	$^{Cap}/_{NDS\ Z}$	1.94	1.76		
	$^{Cap}/_{LRFD\ Z}$	0.94	0.86		
	COV	16.4%	11.3%		
10d Common Nail	$^{Cap}/_{NDS\ Z}$	2.26	2.09	2.36	1.92
	$^{Cap}/_{LRFD\ Z}$	1.10	1.01	1.15	0.93
	COV	18.7%	20.9%	30.2%	16.4%
16d Common Nail	$^{Cap}/_{NDS\ Z}$			2.53	1.90
	$^{Cap}/_{LRFD\ Z}$			1.22	0.92
	COV			26.0%	19.8%

Table 4.47: Observed factors of safety, over-strengths, and associated COVs for solid wood, nailed connections. Safety factors of NDS tabulated values are also given.

	SPF	SYP
$^{Cap}/_{NDS\ Z}$	2.04	1.94
$^{Cap}/_{LRFD\ Z}$	0.99	0.94
COV	19.4%	25.1%
$^{Cap}/_{Tabulated}$	2.14	1.56

Mean over-strengths of bolted connections vary from 1.3 up to 3.0 and are given along with associated COVs in Table 4.48. Just as in Table 4.47, the factors of safety of the NDS tabulated values are also given. The inverse of the same trends observed in C/T ratios are observed here. Over-strengths of connections with thin main members increase significantly with respect to bolt diameter while those with thick side members are not as responsive to the same. Figure 4.31 illustrates these trends. Just as with the other safety factors and over-strengths, the safety factors of NDS tabulated values consistently decrease with respect to main member thickness. On the other hand, safety factors of NDS tabulated values are not significantly affected by bolt diameter. Note that the directions of the bolt diameter and main member material type axes are inverted as compared to those in Figures 4.28 and 4.29.

Table 4.48: Observed factors of safety, over-strengths, and associated COVs for bolted connections. Safety factors of NDS tabulated values are also given.

		Main Member Material			
		SPF 2x4	SPF 4x4	SYP 2x4	SYP 4x4
$^3/_8$" Bolt	$^{Cap}/_{NDS\ Z}$	3.52	2.78	4.02	3.10
	$^{Cap}/_{LRFD\ Z}$	1.68	1.34	1.92	1.49
	COV	8.4%	7.1%	6.0%	8.1%
	$^{Cap}/_{Tabulated}$				
$^1/_2$" Bolt	$^{Cap}/_{NDS\ Z}$	4.38	3.29	5.13	3.14
	$^{Cap}/_{LRFD\ Z}$	2.09	1.58	2.45	1.51
	COV	12.8%	10.2%	10.8%	8.9%
	$^{Cap}/_{Tabulated}$	4.03	2.96	3.70	2.74
$^5/_8$" Bolt	$^{Cap}/_{NDS\ Z}$	5.26	3.73	6.25	3.07
	$^{Cap}/_{LRFD\ Z}$	2.51	1.78	2.99	1.47
	COV	9.2%	12.1%	8.5%	10.8%
	$^{Cap}/_{Tabulated}$	3.83	2.92	4.15	2.48

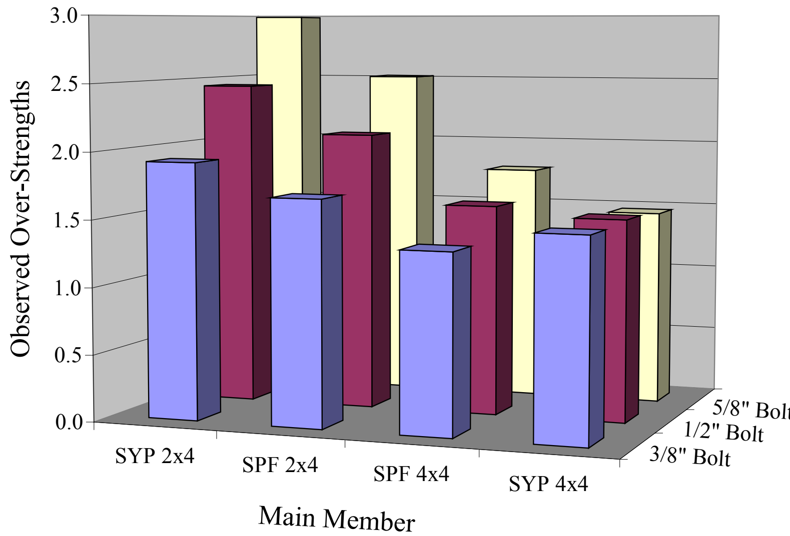

Figure 4.31: Observed over-strengths in bolted connection sets.

Average over-strengths were determined with respect to yield mode in order to evaluate the validity of the K_D factor for nailed connections, and the values given in Table 2.3 for bolted connections, on a capacity basis. Yield Modes I_s, III_s, and IV were observed in nailed connections, while Modes II and III were observed in bolted connections (with the exception of a few which exhibited Mode IV). Differences in average over-strengths with respect to yield mode were less pronounced in nailed connections than in bolted connections. Nonetheless, T-tests detected significant differences between mean over-strengths in all crosswise comparisons. Probability-values associated with these T-tests are given in Table 4.49 along with average over-strengths by yield mode, and COVs. Note the relatively high variabilities in over-strengths of: 1) OSB, plywood, and solid wood connections exhibiting Mode IIIs, and 2) bolted connections exhibiting Mode II. For OSB, plywood, and solid wood members, this reflects the high within-set variability observed in the two connection sets with $^{23}/_{32}$" OSB side members. For bolted connections exhibiting Mode II, the high variability associated with the average over-strength is caused by between-set variability, predominately with respect to bolt diameter. Only in the case of OSB, plywood, and solid wood connections exhibiting Mode IV was the average over-strength less than 1.0 (i.e., the LRFD reference lateral resistance is an unconservative estimate of capacity resistance). Values given for Mode III in this table are broken into three categories: 1) those observed in nailed hardboard, fiberboard, and gypsum wallboard connections, 2) those observed in nailed OSB and plywood connections, and 3) those observed in bolted connections. These were necessarily separated because of differences in material properties and connection behavior. Probability-values associated with T-tests comparing mean over-strengths of these three categories confirmed their differences (Table 4.50). The fact that over-strengths observed in Mode III-yielding hardboard and bolted connections are comparable is merely coincidence. These comparatively high values (as compared to those of nailed connections in OSB and plywood) are brought about by different phenomena. In gypsum wallboard, fiberboard, and hardboard, the elevated over-strengths are brought about by the bearing compaction phenomenon which increases with respect to connection slip. In bolted connections, it is explained by the fact that friction between the two members accounts for an increasingly greater percentage of the total connection resistance as connection slip increases.

Table 4.49: Average observed factors of safety, over-strengths, and associated COVs for each yield mode; with associated p-values of T-tests comparing mean values.

	Nailed Connections				Bolted Connections	
	Gypsum Wallboard, Fiberboard, and Hardboard		OSB, Plywood, and Framing Members (Solid Wood)			
Mode:	I_s	III_s	III_s	IV	II	III
$^{Cap}/_{NDS\ Z}$	3.25	3.09	2.17	1.92	4.25	2.95
$^{Cap}/_{LRFD\ Z}$	1.58	1.50	1.05	0.93	2.03	1.42
COV	17.4%	15.5%	25.8%	17.7%	25.7%	8.5%
p-value	0.007		0.001		0.000	

Table 4.50: P-values associated with T-tests for comparison of mean observed factors of safety in various connection configurations exhibiting Mode III yield.

	Connection Type		
	Nailed: Hardboard	Nailed: OSB and plywood	Bolted
$^{Cap}/_{NDS\ Z}$	3.09	2.17	2.95
$^{Cap}/_{LRFD\ Z}$	1.50	1.05	1.42
COV	15.5%	25.8%	8.5%
p-value	0.000		0.000
	0.032		