

Model Validation

11.1 General

The hysteresis model of MULTBOLT was calibrated to test results of single-bolt joints. To validate MULTBOLT, predictions of multiple-bolt joint behavior are made, based on the single-bolt calibration, and the results are compared with results obtained from experiments of multiple-bolt joints. Thus, numerous experiments were conducted as described in detail in the previous chapter. Although the test program was quite comprehensive, it was not exhaustive. To limit the number of tests and keep the experimental phase of this study within reasonable limits, no basic property tests other than specific gravity and moisture content were carried out. An exhaustive validation is only possible if all material properties are known at various locations, especially in the vicinity of the fasteners. Yet this task is virtually impossible to achieve. For example, actual material strength values for a specimen that is used in the model validation process cannot be attained since only one material strength property can be tested on a given specimen attributed to the destructive nature of the experiment. Thus, rather than attempting to validate the model against a single known case, MULTBOLT was validated against the average response of several experiments. This serves the purpose of reducing the number of tests necessary, because it opens up the possibility to utilize average material properties reported in the literature. Once the accuracy of MULTBOLT has been thoroughly tested, predictions of the commonly used 5 percent exclusion limit can be made using Monte Carlo simulation.

11.2 Global Error

Numerical computations are not exact due to round-off errors resulting from the use of a finite number of digits, and on account of truncation errors, which result from approximations (Rade and Westergren 1999). Repeated runs of MULTBOLT with identical settings resulted in differences of numerical values of less than 10^{-12} . But if the input function is unidirectional, at larger displacements, the solver LSODE produces significant numerical noise. As testified by identical results from repeated runs, the numeric noise is not a random error, however. The noise level changes dependent on the error control used in LSODE. Additional error is introduced by noisy displacement input. The solver LSODE requires the specification of a relative and absolute

error (Hindmarsh 1983). Throughout this work absolute error control of 10^{-12} was used. Better results may be achieved with other error control combinations (i.e. relative error and absolute error control). Furthermore, it is suspected that the numeric noise is hysteresis-parameter and input function specific. If this is the case, then it would be optimal if error control is adapted to each problem solved, which requires a subroutine written by the user. The quantification of the effect of different error control requires considerable experimentation with input parameter combinations, which is beyond the scope of this work but is a necessary part of future work.

11.3 Validation Process and Results

Recall that the modified hysteresis model introduced in Chapter 5 was fit to single-bolt joints with southern pine members yielding in Mode II and Mode IV. The failure model described in Chapter 8 was calibrated to the average response of the single-bolt joints tested yielding in Mode II. It should be further noted that the failure model merely initiates failure but does not predict post-failure behavior. An arbitrary 50 percent load drop per fastener was programmed and is executed when failure is detected. It is clear then that post-capacity performance should not be included in the validation process. The stochastic model presented in Chapter 9 introduces variability to MULTBOLT and permits the comparison of the two samples obtained through testing and by running the model several times, respectively. Therefore, MULTBOLT should be able to accurately predict the expected load-displacement function of the tested 3- and 5-bolt joints yielding in Mode II and possibly the load-displacement relation of the 3- and 5-bolt joints that were supposed to yield in Mode IV but exhibited Mode III and Mode II yield (refer to Chapter 10).

11.3.1 Input Data

Basic input data with which MULTBOLT was validated consisted of the same joint geometries as the respective test configuration, average material properties as reported in the literature, and a coefficient of variation describing the between-member E-modulus variation equal to the variability associated with the bending strength of 150 tests conducted on full size southern yellow pine lumber graded Number 2 (Loferski 2000). Input data along with the proper reference, if applicable, are listed in Table 11.1.

Table 11.1: Basic input parameters used to validate MULTBOLT.

Input	Value	Unit	Reference
E_{para}	10.31283322	kN/mm ²	Bodig & Jayne (1982)
$COV_{E_{para}}$	32	%	Loferski (2000)
<i>angle of friction</i>	30	degrees	Jorissen (1998)
<i>bolt yield moment</i> ⁽¹⁾	105.9232772	kN mm	NDS (AF&PA 1997)
<i>bolt «</i>	12.7	mm	
<i>nbolt</i>	1 or 3 or 5		
<i>member thickness</i>	38.1 or 88.9	mm	
<i>member width</i>	139.7	mm	
<i>spacing</i>	50.8	mm	
<i>spacing COV</i>	0.5	%	(estimated)
<i>oversize</i>	1.5875	mm	
<i>yield mode</i>	II or III or IV		
<i>end distance</i>	88.9	mm	

⁽¹⁾Yield moment was computed from published yield strength.

11.3.2 Visual Validation

11.3.2.1 Unidirectional (Monotonic) Displacement Input

There is a strong indication that MULTBOLT is capable of predicting uni-directional performance as well, although the hysteresis model was fit to cyclic data. MULTBOLT describes an equivalent physical system and is therefore relatively independent of the input function, once properly calibrated. Unfortunately, only limited data are available to validate uni-directional predictions. Just two multiple-bolt configurations, 5-bolt yielding in Mode II and 5-bolt predicted to yield in Mode IV, were tested monotonically. Useful data is further reduced because data from unidirectional joint tests of Mode IV-type joints exhibit some peculiarities. Most likely attributed to the inferior lumber (boxed heart, specific gravity 20% below average, large portions of juvenile wood), average monotonic stiffness *and* capacity of Mode IV joints were actually lower than for Mode II-type joints (Figure 11.1)(refer to Section 10.5). This is despite the fact that member cross sections were substantially larger for joints predicted to yield in Mode IV. Although MULTBOLT permits the input of lower property values, the impact is currently limited. Since hysteresis parameters are tied to a finite number of single-bolt tests, joint stiffness can only be as low as the softest single-bolt joint tested, even if material properties are decreased by 20 percent

(see Section 9.3 for details). It is not surprising then, that attempts to fit MULTBOLT to monotonically stressed Mode IV-type joints produced unsatisfactory results (Figure 11.2).

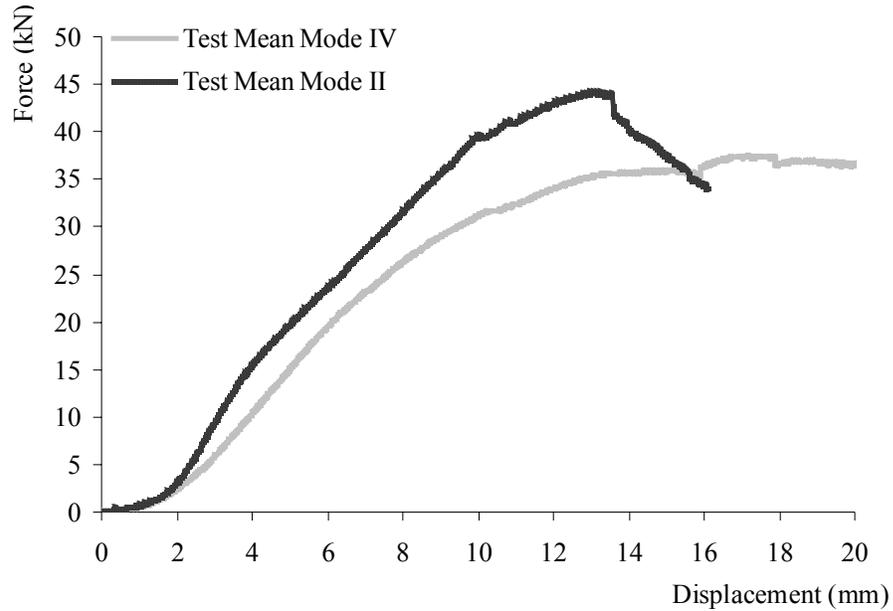


Figure 11.1: Average load-displacement curves for specimens yielding in Mode II and Mode IV, respectively.

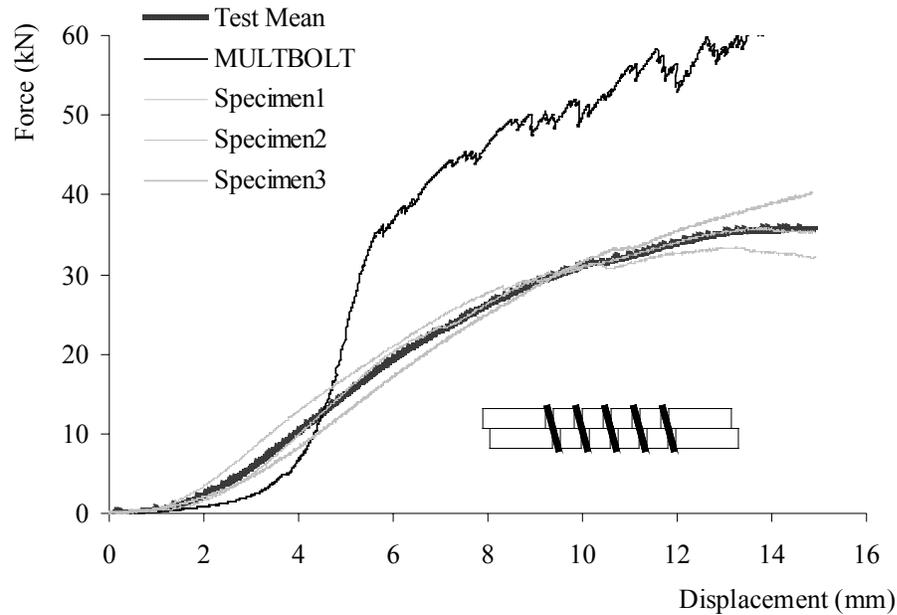


Figure 11.2: Unsatisfactory fit of MULTBOLT predictions to unidirectional displaced specimens designed to yield in Mode IV due to the use of low-dense wood containing large amounts of juvenile wood. Joint was a 5-bolt joint, material property values were lowered by 20% to conform to low specific gravity and strength of test specimens. Significant numerical noise develops at larger displacements.

No such anomalies were observed on joints yielding in Mode II. Members were thinner, average specific gravity was comparable to established values of southern pine, and defects such as juvenile wood or drying cracks were absent within the joint region. With the same unidirectional displacement function, MULTBOLT seems to predict well average monotonic performance of the 5-bolt joint configuration yielding in Mode II (Figure 11.3). Although predicted data lie within the bounds of test data, stiffness and capacity predictions seem to be within the upper segment of test data. However, limited sample size and high variation call for the need of further testing.

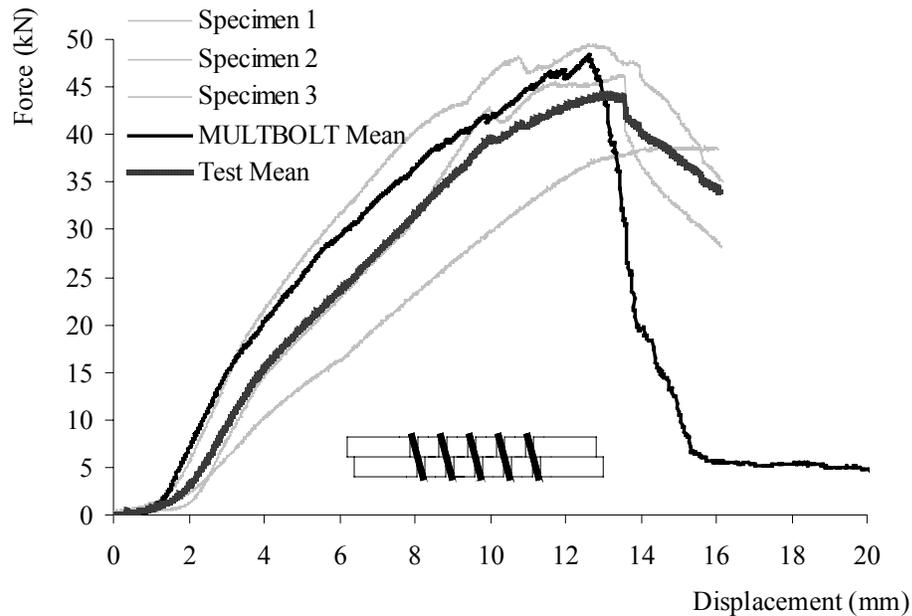


Figure 11.3: Comparison of average monotonic load-displacement plot to average monotonic prediction by MULTBOLT. Tests exhibited high variation as testified by data of individual specimens. Joint was a 5-bolt joint yielding in Mode II. Only three joints were tested. MULTBOLT was run ten times.

11.3.2.2 Cyclic Displacement Input

Relevant load-displacement and total absorbed energy plots are exhibited in Figures 11.1 through 11.12. Total absorbed energy represents the continuous integral of the resisted force over the displacement. Note that the curves shown are average curves of ten tests and ten runs of MULTBOLT for the configuration in question (load was averaged).

Recall from Chapter 10 that the observed yield mode was Mode III and even Mode II in some fasteners when large member ($140 \times 89 \text{ mm}^2$) joints of more than one bolt in a row were tested. Oversized holes, low embedment strength and higher than average (reported) bolt yield strength substantially increased the likelihood of Mode III yield for these joints. Nevertheless, joints predicted to yield in Mode IV but actually exhibited Mode III as the highest yield mode were included in the validation process. This is based on the hypothesis introduced in Chapter 10 that higher yield modes evolve from lower modes in joints containing oversized holes. Hence, single bolt joints exhibited Mode IV yield because end distances were much larger than minimum spacing in multiple-bolt joints and thus, premature failure did not occur and the fasteners were able to develop two plastic hinges at large displacement amplitudes. This is why the Mode IV

single bolt data used as input for the hysteresis model is still valid to predict multiple bolt behavior even though the highest yield mode reached in these joints was only Mode III. The hysteresis model and the failure model are independent. Thus, while MULTBOLT may describe a hysteresis of a Mode IV – type joint, the failure model can still initiate failure based on Mode III yield with the result that the joint reaches maximum load much earlier than a Mode IV prediction would have indicated. Since input was displacement, capacity predictions should therefore be valid.

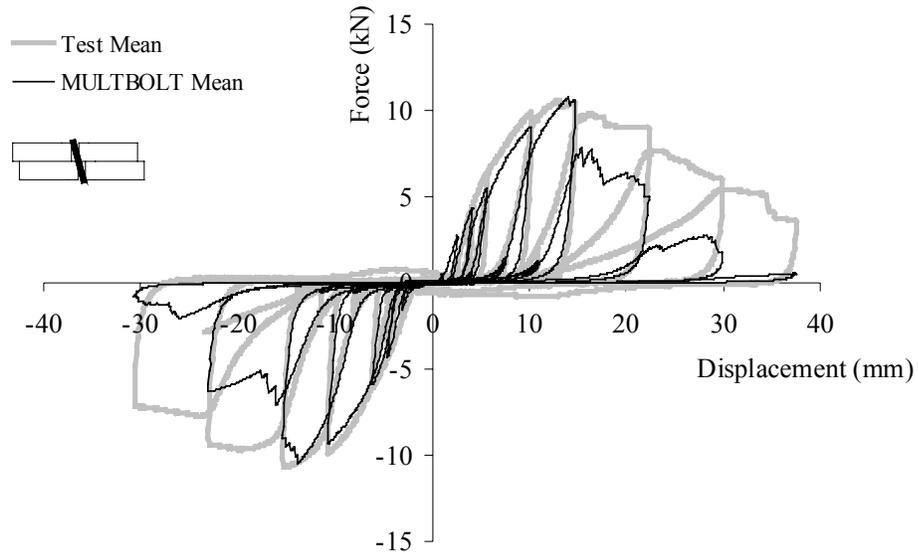


Figure 11.4: Comparison of average load-slip plot of 10 test results with average result of 10 MULTBOLT runs. Joint is a single bolt joint yielding in Mode II.

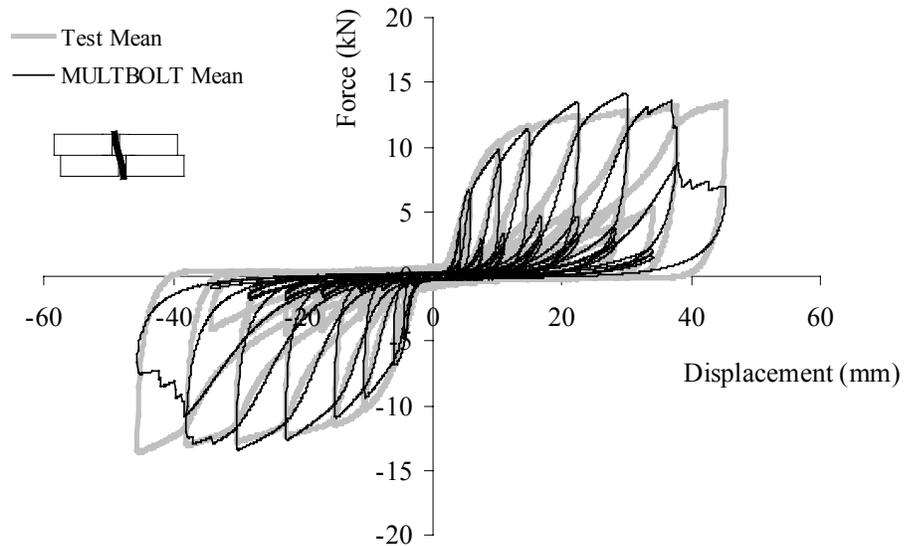


Figure 11.5: Comparison of average force load-slip plot of 10 test results with average result of 10 MULTBOLT runs. Joint is a single bolt joint yielding in Mode IV.

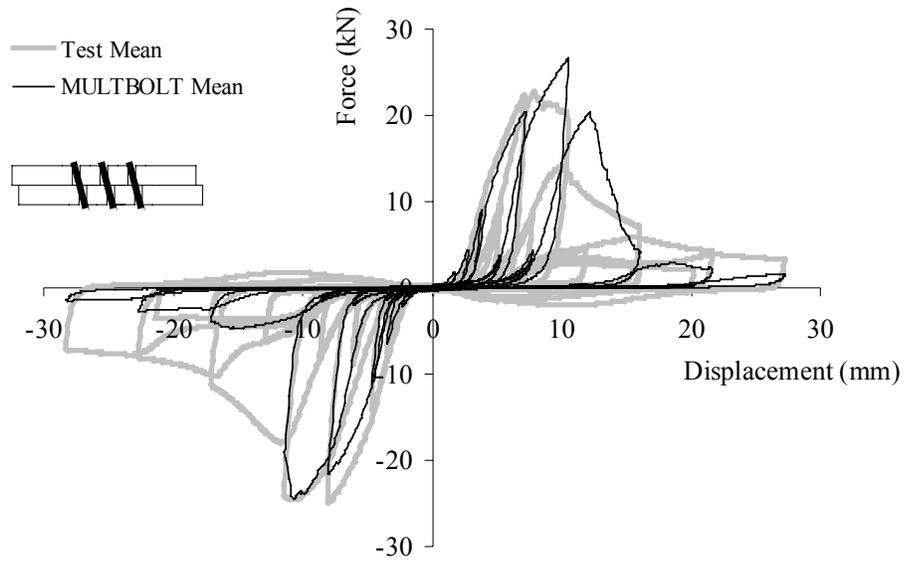


Figure 11.6: Comparison of average load-slip plot of 10 test results with average result of 10 MULTBOLT runs. Joint is a 3-bolt joint yielding in Mode II.

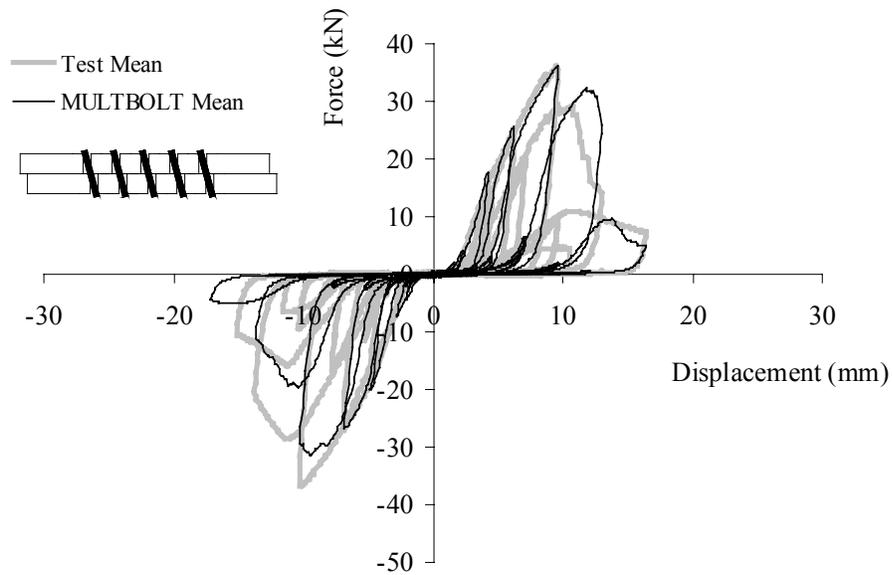


Figure 11.7: Comparison of average load-slip plot of 10 test results with average result of 10 MULTBOLT runs. Joint is a 5-bolt joint yielding in Mode II.

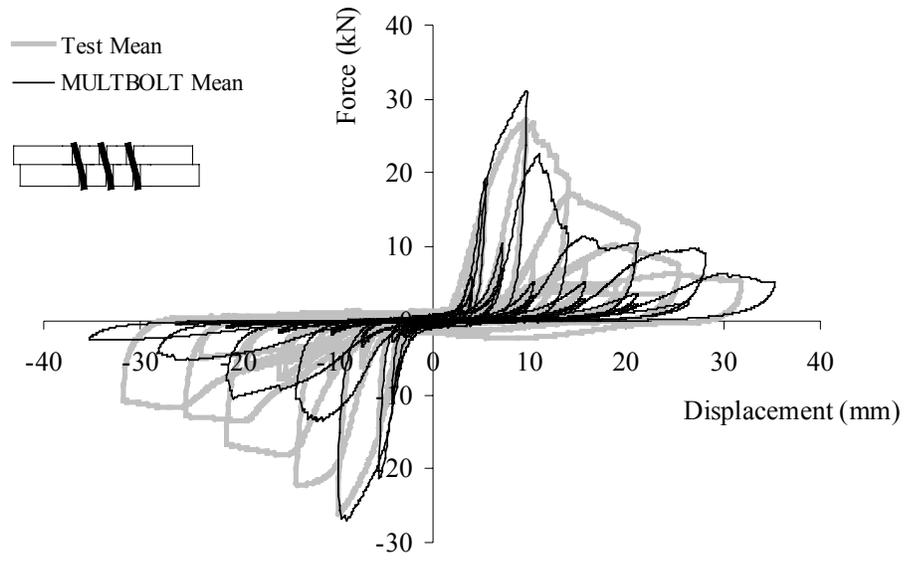


Figure 11.8: Comparison of average load-slip plot of 10 test results with average result of 10 MULTBOLT runs. Joint is a 3-bolt joint yielding in Mode III.

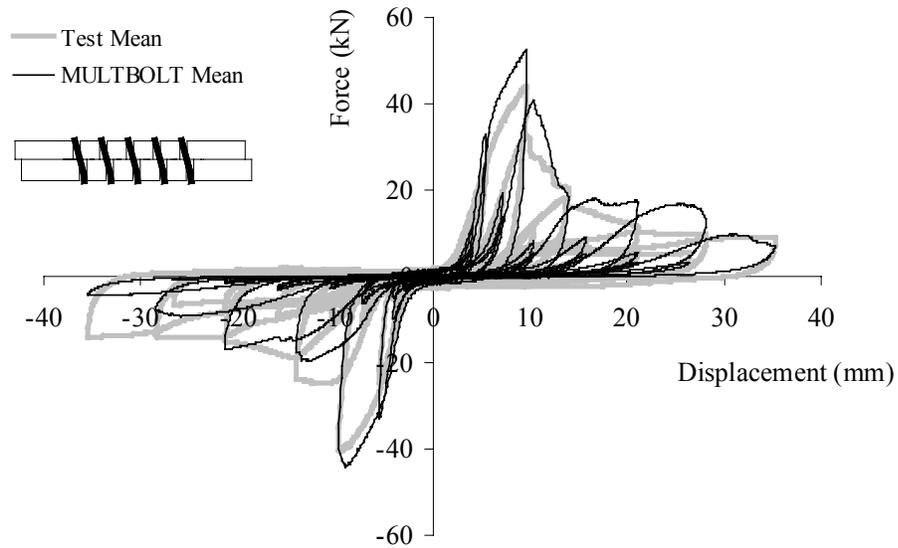


Figure 11.9: Comparison of average load-slip plot of 10 test results with average result of 10 MULTBOLT runs. Joint is a 5-bolt joint yielding in Mode III.

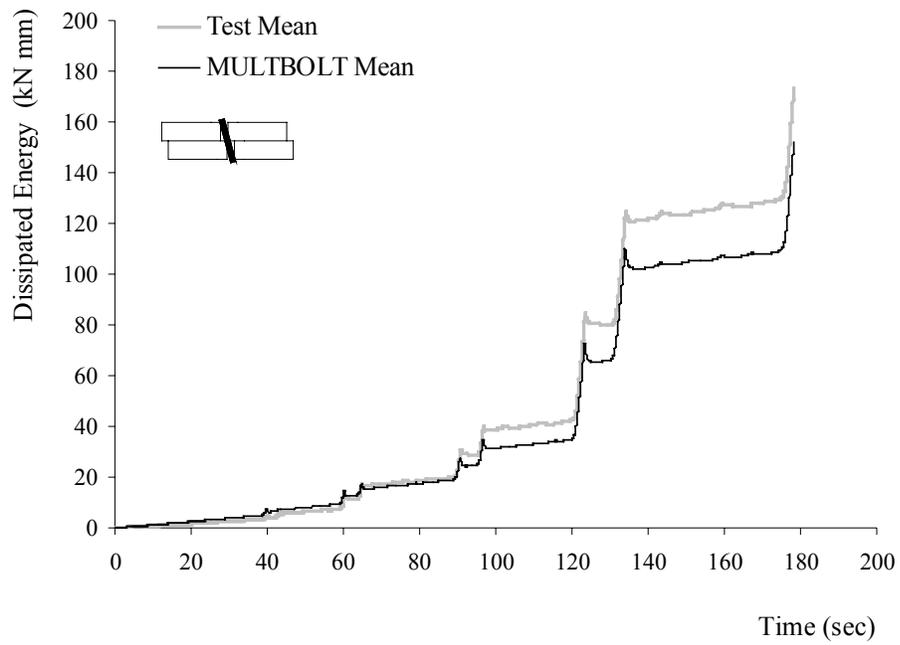


Figure 11.10: Comparison of average absorbed energy up to capacity of 10 test results versus 10 MULTBOLT runs. Joint is a single-bolt joint yielding in Mode II.

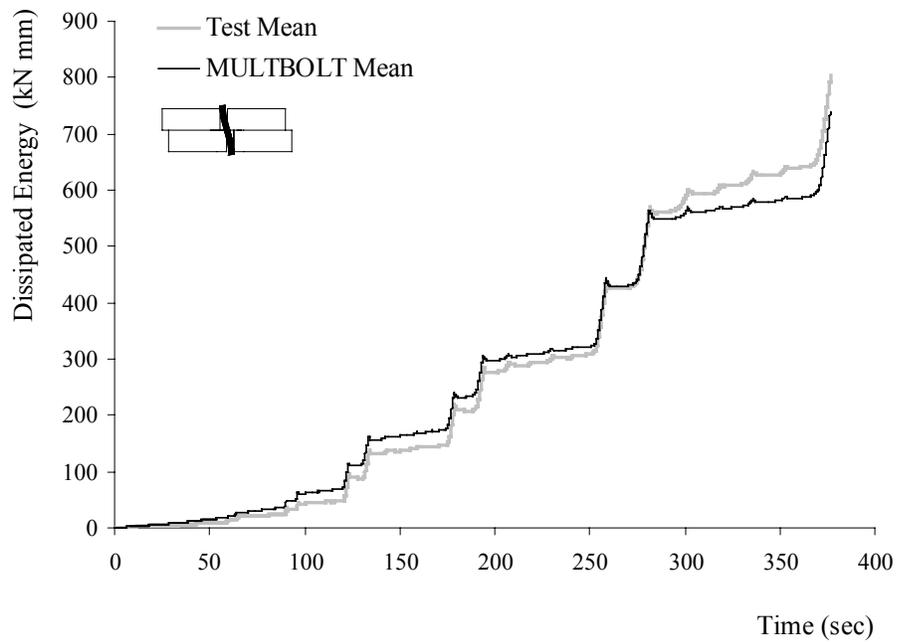


Figure 11.11: Comparison of average absorbed energy up to capacity of 10 test results versus 10 MULTBOLT runs. Joint is a single-bolt joint yielding in Mode IV.

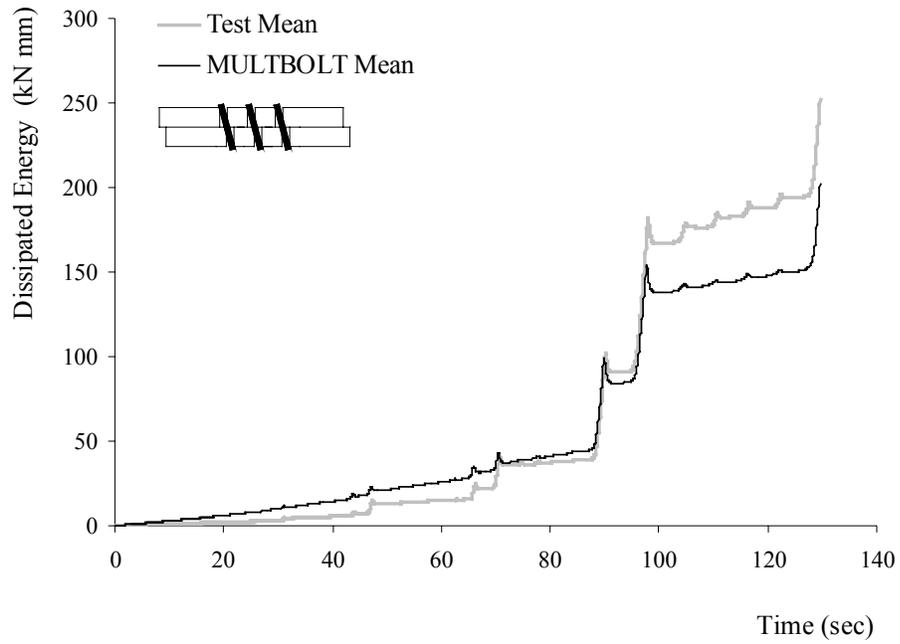


Figure 11.12: Comparison of average absorbed energy up to capacity of 10 test results versus 10 MULTIBOLT runs. Joint is a 3-bolt joint yielding in Mode II.

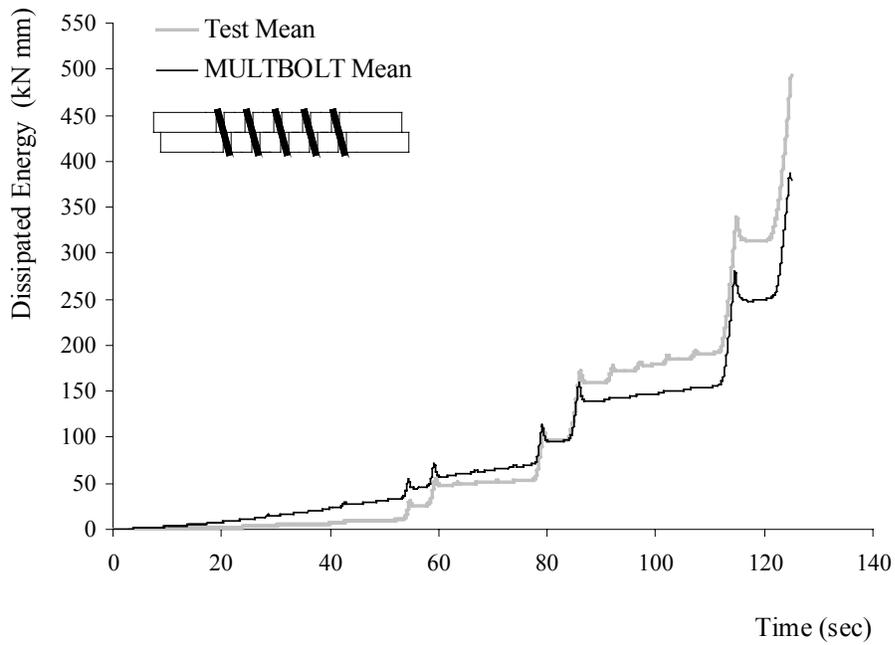


Figure 11.13: Comparison of average absorbed energy up to capacity of 10 test results versus 10 MULTIBOLT runs. Joint is a 5-bolt joint yielding in Mode II.

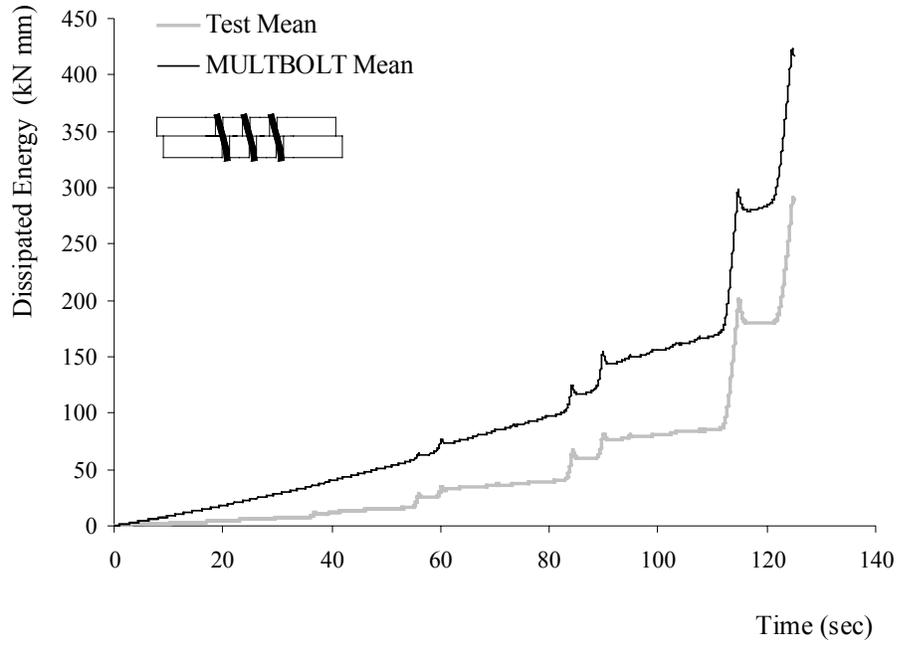


Figure 11.14: Comparison of average absorbed energy up to capacity of 10 test results versus 10 MULTBOLT runs. Joint is a 3-bolt joint yielding in Mode III.

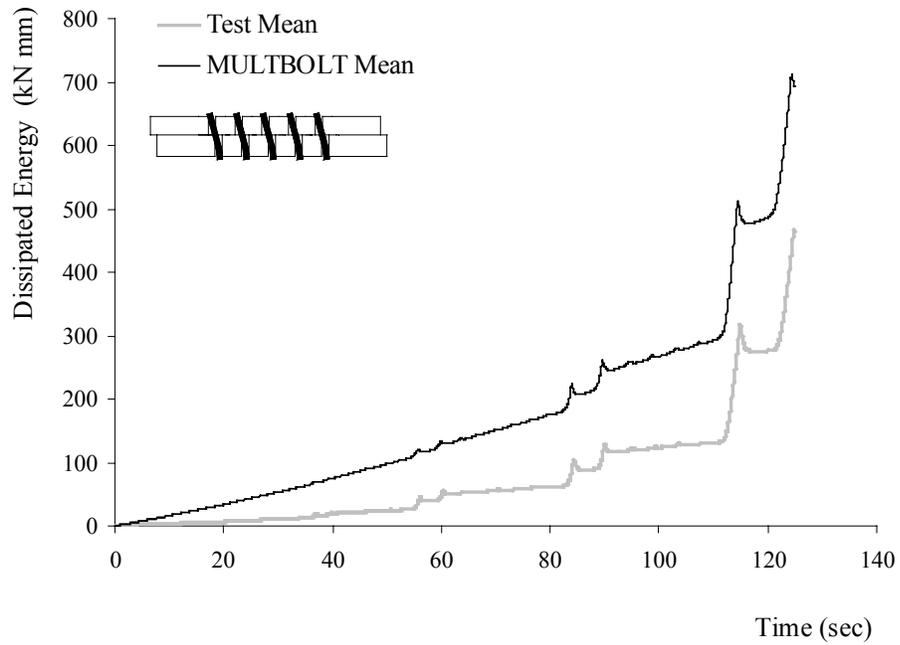


Figure 11.15: Comparison of average absorbed energy up to capacity of 10 test results versus 10 MULTBOLT runs. Joint is a 5-bolt joint yielding in Mode III.

Overall, for all yield modes presented, MULTBOLT shows good agreement with experimental data up to joint capacity. Initial observations indicate that stiffness and predicted capacities are within the margin of error (statistical evidence is presented in the next section). Observe that the failure model initiates failure on single-bolt Mode IV-type joints at displacements less than 40 mm, whereas test data show no signs of failure up to the largest displacements tested (Figure 11.5). The minimum average bolt yield strength was used as published in the NDS (AF&PA 1997) for A 307 bolts. However, bolt yield strength may vary greatly and may actually be substantially higher. A higher yield strength shifts the location of the plastic hinges towards the shear plane and less wood is displaced triggering failure at larger displacement amplitudes¹.

Energy predictions for Mode III yield are relatively poor with MULTBOLT significantly overestimating absorbed energy. In general, MULTBOLT seems to over predict absorbed energy at small displacement amplitudes (earlier in the test) but underestimates energy at larger displacement amplitude before capacity is reached. Mode III energy prediction is consistently over predicted probably because not all bolts within the joint arrived at Mode III yield before failure. The reason for the under prediction at larger amplitudes for Mode II-type joints lies in the fact that MULTBOLT does not account for frictional forces caused by the slipping bolt. Observe that during unloading after the elastic wood deformation has “sprung back”, the testing machine often had to exert force on the joint to overcome friction which is suggested by the force changing sign at relatively large displacements. Because absorbed energy is a continuous summation of force times displacement per time step, the error is compounded and increases further into the test. Moreover, due to growing slack at increasing displacement amplitudes, energy absorbed caused by forces to overcome friction of the slipping fasteners increases at larger displacements.

11.3.3 Statistical Validation

Simple t-tests were carried out comparing the sample means of tested and predicted capacity, and tested and predicted absorbed energy near capacity. The p-value given in the tables below gives the probability of wrongly rejecting the null hypothesis (two means are equal). In other words, it is the probability of obtaining the observed difference in means just by chance

¹ As of this writing, actual bending tests to determine bending strength of bolts used in experiments have not been conducted by Anderson (2001).

given that the values stem from the same distribution. Thus, a large p-value (> 0.05) does not allow the conclusion that the observed means are different.

In addition to conducting hypothesis testing, correlation up to capacity was computed between average model predictions and average test data (Pearson's coefficient, assuming normal data). This was possible because the same displacement input was used for both model computations and tests of a certain joint configuration. If MULTBOLT predicted exactly the forces recorded during tests at each displacement increment, then a plot of forces predicted by MULTBOLT versus forces measured during tests would follow a straight line emanating from the origin with slope equal to 1.0. In other words, there would be a perfectly linear relationship between MULTBOLT predictions and tests results. Hence, a correlation coefficient close to 1.0 would indicate a good prediction of measured values.

Whereas for visual validation load-displacement curves were pooled and simply averaged, statistical validation parameters of interest were computed from data of each specimen and then averaged to avoid displacement bias. For example, one specimen may reach a load extremum at 20 mm in contrast to another specimen where maximum load was reached at 10 mm. If the force values of the two curves are averaged per displacement point (again, this is possible since the same displacement input was used per configuration) the resulting capacity of the average curve may occur at 17 mm displacement and may not be equal to the average of the two individual capacities. This explains why mean capacities computed below are likely to differ from the capacities of the average load-displacement functions revealed in the previous section.

11.3.3.1 Unidirectional Statistics

There is high correlation between average predicted unidirectional load values and average values obtained from testing up to capacity (Table 11.2). Furthermore, MULTBOLT accurately predicts monotonic capacity of the 5-bolt Mode II configuration (Table 11.3). While the model seems to overestimate maximum load somewhat, relative error is less than 10 percent. In comparison to a simple prediction obtained by the multiplication of average capacity from monotonic single-bolt tests (Table 11.3), MULTBOLT values lie much closer to actual values. Multiplication of single-bolt capacity by the number of bolts contained in the respective multiple-bolt joint results in substantial overestimation of capacity.

Table 11.2: Correlation between MULTBOLT predictions and results of unidirectional 5-bolt joint tests yielding in Mode II.

5 Bolt Mode II Correlation		
	Actual	MULTBOLT
Actual	1.0	
MULTBOLT	0.992	1.0

Table 11.3: Evaluation of average , monotonic capacity prediction by MULTBOLT. Also shown is maximum load computed by multiplying single-bolt capacity by the number of bolts contained in the multiple-bolt joint.

5 Bolt Mode II				
	Mean (kN)	COV (%)	Actual / Predicted	p-value (two-tailed t-test, σ_1 σ_2)
Actual	44.89	12.0		0.314
MULTBOLT	49.10	12.4	0.914	
$5 \cdot \bar{F}_{\text{single, Mode II}}$	77.52		0.579	

11.3.3.2 Reversed Cyclic Statistics

A reversed cyclic test based on a symmetric protocol (equal displacement amplitudes in positive and negative displacement direction) yields two load extrema, one positive and one negative. The failure model predicts failure based on fastener displacement only. This means that positive and negative load extrema are a function of the load predicted by the hysteresis model and the displacement at which failure is initiated. Since for most practical purposes absolute capacity is of interest, the two values were averaged (using absolute values). The average absolute capacity was determined from absolute capacities of all specimens of the same configuration. The value was compared to the average absolute capacity computed from ten MULTBOLT runs of the same configuration. In order to exclude the extreme variable post-capacity behavior, absorbed energy was computed for each specimen at the time where the weakest specimen of a given configuration reached an extremum first (could be positive *or* negative). In other words, for a specific specimen group, energy was computed at the same time for all specimens. It was initially attempted to compare the absorbed energy at capacity of each

specimen. However, the results were inconclusive because capacities were reached at different times, which introduced significant variability.

For all joint configurations predicted, MULTBOLT yields values strongly linearly correlated with test results. The lowest percentage of variation (obtained by squaring the correlation coefficient) explained by MULTBOLT is 81 percent for the 5-bolt joint yielding in Mode III. Other values are well over 90 percent. In addition, cyclic capacity prediction by MULTBOLT is good and within the bounds of error as indicated by the non-significant p-values listed in Table 11.5. For all joints tested, average capacity predictions are within 11 percent of the average test value. The table also reveals capacities predicted for multiple-bolt joints by simply multiplying the respective mean capacity from single bolt joints by the number of bolts. This results in substantial overestimation with values deviating as much as 38 percent from test values in contrast to the much closer values produced by MULTBOLT. Except for joints yielding in Mode III, MULTBOLT seems to underpredict average capacity somewhat. The different behavior of Mode III may be attributed to the hysteresis model input data which was intended to predict Mode IV yield. Maximum load prediction is influenced by the hysteresis model and the failure model in MULTBOLT. The failure model predicts the displacement at which the load is reduced. Load level is computed by the hysteresis model.

Table 11.4: Correlation between MULTBOLT predictions and results of unidirectional 5-bolt joint tests yielding in Mode II.

1 Bolt Mode II Correlation		
	Actual	MULTBOLT
Actual	1.0	
MULTBOLT	0.991	1.0

1 Bolt Mode IV Correlation		
	Actual	MULTBOLT
Actual	1.0	
MULTBOLT	0.969	1.0

3 Bolt Mode II Correlation		
	Actual	MULTBOLT
Actual	1.0	
MULTBOLT	0.967	1.0

5 Bolt Mode II Correlation		
	Actual	MULTBOLT
Actual	1.0	
MULTBOLT	0.962	1.0

3 Bolt Mode III Correlation		
	Actual	MULTBOLT
Actual	1.0	
MULTBOLT	0.970	1.0

5 Bolt Mode III Correlation		
	Actual	MULTBOLT
Actual	1.0	
MULTBOLT	0.901	1.0

Table 11.5: Evaluation of average, cyclic capacity prediction by MULTBOLT. Also shown is maximum load computed by multiplying single-bolt capacity by the number of bolts contained in the multiple-bolt joint.

1 Bolt Mode II				
	Mean (kN)	COV (%)	Actual / Predicted	p-value (two-tailed t-test, σ_1 σ_2)
Actual	12.32	20.9		0.215
MULTBOLT	11.13	12.0	1.107	
1 Bolt Mode IV				
Actual	14.37	21.9		0.805
MULTBOLT	14.11	7.3	1.019	
3 Bolt Mode II				
Actual	26.63	9.9		0.984
MULTBOLT	26.60	13.8	1.001	
$3 \cdot \bar{F}_{\text{single, Mode II}}$	36.96		0.720	
5 Bolt Mode II				
Actual	38.60	10.2		0.167
MULTBOLT	35.52	15.4	1.087	
$5 \cdot \bar{F}_{\text{single, Mode II}}$	61.60		0.627	
3 Bolt Mode III				
Actual	28.08	20.2		0.507
MULTBOLT	29.66	16.0	0.947	
$3 \cdot \bar{F}_{\text{single, Mode IV}}$	43.12		0.651	
5 Bolt Mode III				
Actual	44.46	15.2		0.083
MULTBOLT	49.37	10.2	0.900	
$5 \cdot \bar{F}_{\text{single, Mode IV}}$	71.87		0.619	

As already alluded to and signified by the graphs revealed in the previous section, absorbed energy predictions near capacity are less accurate and are statistically significantly different for the single bolt configuration yielding in Mode IV and for Mode III-type joints (Table 11.6). Nevertheless, not counting Mode III, deviations are less than 16 percent near capacity.

Table 11.6: Evaluation of average absorbed energy prediction by MULTBOLT.

1 Bolt Mode II				
	Mean (kN mm)	COV (%)	Actual / Predicted	p-value (two-tailed t-test, σ_1 σ_2)
Actual	82.11	15.7		0.075
MULTBOLT	71.14	18.3	1.154	
1 Bolt Mode IV				
Actual	188.11	19.2%		0.024
MULTBOLT	219.51	6.3%	0.857	
3 Bolt Mode II				
Actual	81.98	10.1%		0.089
MULTBOLT	92.29	17.1%	0.888	
5 Bolt Mode II				
Actual	277.08	18.1%		0.066
MULTBOLT	240.35	12.6%	1.153	
3 Bolt Mode III				
Actual	142.02	20.3%		0.000
MULTBOLT	242.14	9.1%	0.587	
5 Bolt Mode III				
Actual	208.44	35.1%		0.000
MULTBOLT	425.48	8.1%	0.490	

11.3.3.3 Unidirectional versus Cyclic

A very important observation can be made when comparing monotonic to cyclic predictions of the 5-bolt joint configuration yielding in Mode II. MULTBOLT correctly predicts higher capacity for joints stressed monotonically. The reason for this is the lower energy demand of monotonic tests resulting in reduced system degradation. This is a true extrapolation and, if substantiated by further tests, may make the model indeed versatile in terms of applicable displacement input.

11.4 Validation Summary

MULTBOLT seems to accurately predict the load-deflection relation of multiple-bolt joints yielding in Mode II both for reversed cyclic and unidirectional displacement input. Probably as a result of defects contained in the larger members (drying checks and juvenile wood and associated lower specific gravity) and most likely because yield modes varied within joints using larger members, MULTBOLT had more difficulties predicting the absorbed energy of higher yield modes. However, load-displacement predictions are adequate. Despite the fact that the current failure model does not account for varying yield modes within a given joint, good predictions were achieved by inputting the highest mode that was actually observed.

Based on the above validation, there is confidence that model predictions are valid for changing numbers of bolts per joint, since good predictions were achieved with 1-, 3-, and 5-bolt joints. In addition, there is confidence that MULTBOLT accurately predicts the effects of changes in bolt spacing. MULTBOLT treats end distances as fastener spacing. Thus, since accurate predictions were obtained using essentially two different spacings including end distances of single-bolt joints (seven times bolt diameter) and the significantly smaller fastener spacing (four times bolt diameter), there is assurance that predictions for other spacings are valid. There is also increased confidence that MULTBOLT predictions are valid for varying displacement input as testified by the good results obtained for unidirectional displacement functions and the good results obtained for cyclically displaced multiple-bolt joints. Based on different monotonic failure displacements obtained during tests, the displacement function applied for cyclic tests changed from joint configuration to joint configuration. In addition, MULTBOLT does not seem to have problems with noisy input data. However, validation tests using rapidly varying displacing functions that cause inertia effects (such as earthquake records) should be carried out before attempting to predict these drastically different cases.

In summary, MULTBOLT is currently capable of predicting the performance of single shear multiple-bolt joints in southern pine lumber containing one row of bolts. Bolt diameter and

total oversize are currently fixed at 12.7 mm and 1.6 mm, respectively. Two choices of member thickness are available at the present stage, 89 mm and 38 mm. Parameters that can be varied are member width, bolt spacing and end distance for each bolt, number of bolts, input function, and material properties around each fastener. In addition, stochastic variation may be attached to bolt spacing, which determines variability in slack per bolt and direction. Variation may also be attached to modulus of elasticity parallel to the grain, which is linked to material strength values and hysteresis shape.

11.5 Other Cases

MULTBOLT is currently limited to only one fastener and slack size, two member thicknesses as well as one species because no correlation and covariance matrix has been established that links hysteresis shape parameters to other cases, which would allow extrapolation to cases not tested. It is important to realize that MULTBOLT does not have to be changed to include other joint configurations except for joints with more than one row of fasteners. What is more, while MULTBOLT is presently limited to the joint configurations with which hysteresis parameters were estimated, the failure model does not have these limitations. The failure model is capable of predicting failure for any single-row joint configuration and could be used as stand-alone model or it could be easily integrated into other multiple- or single-bolt models.

The influence of two or more rows was not accounted for at all. Very limited data is available that show the effect of row interaction especially under cyclic loading. However, the inclusion of more than one row is mostly a matter of generalizing the failure model once interaction effects become clear.

Since asymmetry of the single shear joint and the resulting moments were neglected, MULTBOLT can be used to predict the response of symmetric double shear joints once the relation of hysteresis parameters to joint dimensions are modeled.