Chapter 12

Parametric Study on Group Action

12.1 General

Main input variables of MULTBOLT are number of fasteners, fastener spacing, end distance, member width and thickness, material property variation, and spacing variation. The influence of the main parameters and effects of their variation on group action are studied in this chapter. The purpose of the parametric study is not so much to present absolute predictions but rather to investigate the relative effect of various parameters on joint response.

Comparisons of MULTBOLT predictions with group action characteristics outlined in the NDS (AF&PA 1997) are made. It is important to realize, however, that this study is concerned with group action at limit state (i.e. maximum load) and not, as is the case with NDS equations, at proportional limit. The NDS equations were derived by Zahn (1991) from linear elastic analysis advanced by Lantos (1969), which is described in Section 3.3.1. Nevertheless, comparisons with NDS predictions are made to highlight a principal issue. It is shown below that group action at limit state differs in mechanism from group action at proportional limit. The inclusion of group action in the design process of multiple-bolt joints is of mere safety reasons. It seems unreasonable then, to base group action on linear elastic analysis, if, as is demonstrated here, the group action effects that cause failure are quite different.

12.2 Effect of Fastener Spacing – No Stochastic Variation

The group action factor describes the effect of number of bolts in a row on normalized joint capacity. That is, total joint capacity divided by the number of fasteners per joint. MULTBOLT was first run with stochastic variation turned off. In other words, material properties were not allowed to vary neither per member nor spatially and spacing was constant between fasteners. The slight variation in the group action factors, as can be observed in the figures below, is caused by numerical error (see Chapter 11)[1]. Member strains increase with increasing number of fasteners because joint forces are higher. Thus, with higher member strains,

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[1] In the figures, data points are connected by lines to enhance clarity. The lines do not represent valid interpolation.

displacements of individual bolts decreases although the input displacement is the same for each joint. The structural model introduced in Chapter 7 accounts for member strains and regulates displacement input of the hysteresis model discussed in Chapter 5. At lower displacements, forces should be correspondingly lower. However, the forces computed by the hysteresis model are not exact. Rather, they are subject to numerical error introduced by the solver LSODE. The error can be directly observed in Figure11.2, where the data exhibit significant numerical noise at larger displacements.

12.2.1 Unidirectional Displacing Function

Fastener spacing has substantial influence on group action (Figure 12.1). With an end distance of 89 mm (= 7D as recommended by the NDS), simulated joints exhibit the largest relative load drop when the number of fasteners is increased from 1 to 2. Except for the joint configuration with bolts spaced at 7D, an increase of the number of bolts from 1 to 2 effectively decreases the shear stress area (see Section 8.3.2) causing higher stresses and consequently failure at smaller displacements. Also, while shear stresses produced by individual fasteners do not interact in MULTBOLT, perpendicular-to-grain stresses do, increasing the stress level if another bolt is added. This explains why there are still group action effects at 7D spacing. Attributed to the stress distribution shape, the interaction of perpendicular-to-grain stresses diminishes at larger spacings (see Section 8.3.1). The relatively large group action effect between one- and two-fastener joints diminishes with increasing spacing.

The effect of member strain on group action as first described by Cramer (1968) and Lantos (1969) is actually very small at limit state. In a joint containing 20 bolts in a row, at approximately 180 kN joint load, the middle bolt experiences a displacement that is less than 1 mm smaller than the displacement computed for the first bolt (Figure 12.2). This is partly because of inelastic material deformations and subsequent load redistribution and partly because of high material stiffness parallel to the grain compared to fastener stiffness. Hence, MULTBOLT predicts that group action changes little with increasing number of bolts and is only influenced by the diminishing interaction effects of perpendicular-to-grain stresses and the level of parallel-to-grain stresses, which impact the Tsai-Wu failure model. The trends shown here are substantiated by experimental results obtained from double-shear joints as reported by Jorissen (1998).

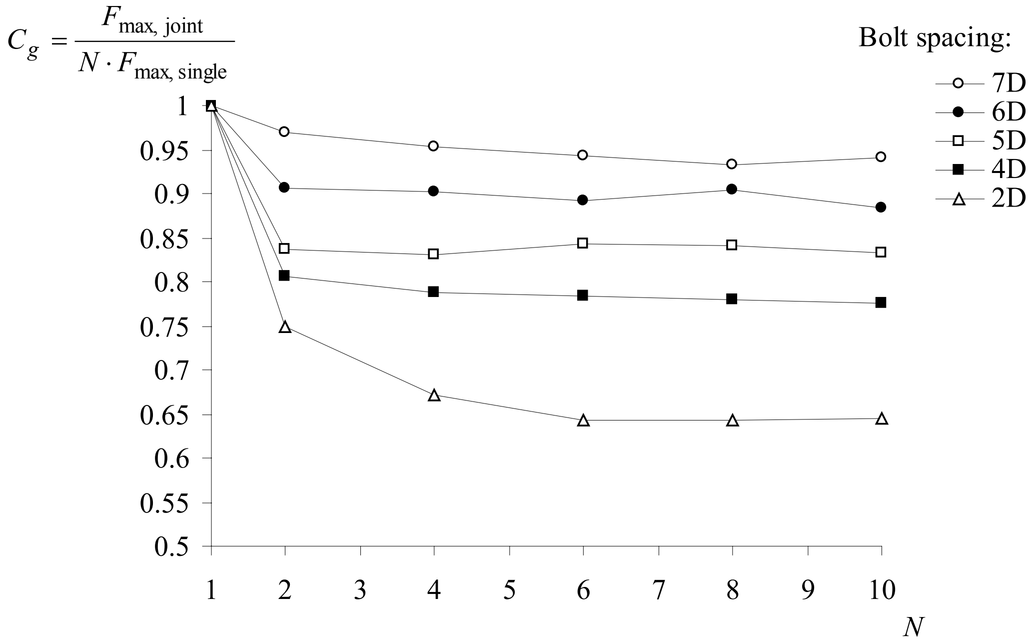

Figure 12.1: Group action effect of joints displaced unidirectionally. *N* denotes the number of bolts in a row. The y-axis represents the predicted group action factor C_g (relative capacity per bolt in a multiple-bolt joint compared with the capacity of a single-bolt joint). Results of joints containing 1, 2, 4, 6, 8, 10 bolts spaced 2D, 4D, 5D, 6D, 7D are shown (bolt diameter D = 12.7 mm, southern pine members 38 x 140 mm^2, end distance = 89 mm).

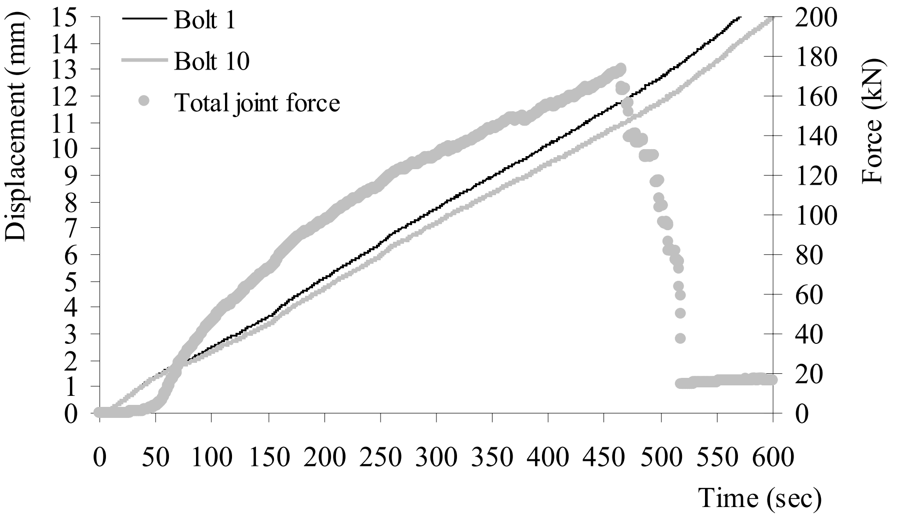

Figure 12.2: Different displacing functions experienced by the first and middle bolt in a 20-bolt joint, due to member strains. Total force resisted by the entire joint over time is also shown.

The trend predicted by MULTBOLT opposes the trend predicted by equations published in the 1997 NDS. Based on proportional limit, the NDS does not predict any group action factor for the joint containing 2 bolts in a row, but group action progressively increases with increasing number of bolts (Figure 12.3). Considering limit state, however, given the findings of this work, both experimental and theoretical, it is hard to envision that two bolts with diameter of 12.7 mm, spaced 4 bolt diameters apart in a joint with common members (38 x 140 mm^2) do not interact, and hence do not negatively affect joint capacity. Furthermore, it is equally implausible that group action *progressively* increases with increasing number of bolts, since it could be shown that the effect of member strains is quite small due to the high stiffness of wood parallel to the grain and load redistribution triggered by inelastic deformations. While the group action effect is much smaller for two-bolt joints if bolt spacing equals minimum end distance, it is substantial if fastener spacing falls well below minimum end distance.

Derived from the understanding that has been gained during the development of MULTBOLT, it seems unreasonable to treat fastener spacing different from end distance in terms of the effect on joint capacity as is currently the case in the NDS. The area of influence of two adjacent bolts is mainly concentrated between the bolts. Although perpendicular-to-the grain stresses induced by a particular bolt are transferred along the members, they are concentrated at the fastener and decrease rapidly away from the fastener. Additionally, shear stresses are not transferred and the hole of the next fastener acts similar to a free end. The interaction of shear stress and tension perpendicular-to-the grain stress in combination with a higher normal stress parallel to the grain than at member ends, makes the distance to an adjacent hole an equally effective parameter as end distance. Thus, for bolted joints, minimum spacing requirements for full capacity should equal minimum end distance.

Most likely attributed to its basis on limit state, group action computed by MULTBOLT appears to be considerably larger than predicted by the NDS. But if compared to other research conducted on three member double shear joints loaded unidirectionally (Jorissen 1998), MULTBOLT seems to underpredict group action factors (Figure 12.4). However, Jorissen's values were derived from experimental data and include material property variability. While predicted trends of MULTBOLT will not change, absolute computed values are based on a limited number of validation tests. Values may be subject to change upon the completion of a more exhaustive validation test program.

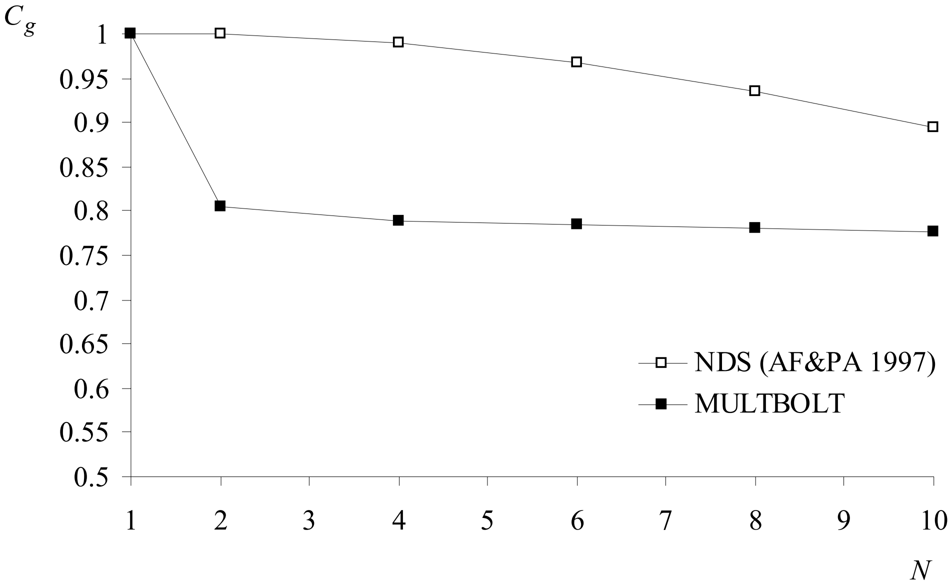

Figure 12.3: Comparison of group action predicted by MULTBOLT with predictions by the NDS (AF&PA 1997). *N* denotes the number of bolts in a row. The y-axis represents the predicted group action factor C_g. Results of joints containing 1, 2, 4, 6, 8, 10 bolts are shown (bolt diameter D = 12.7 mm, southern pine members 38 x 140 mm^2, bolt spacing = 4D, end distance = 89 mm, modulus of elasticity for both members = 10.31 kN/mm^2).

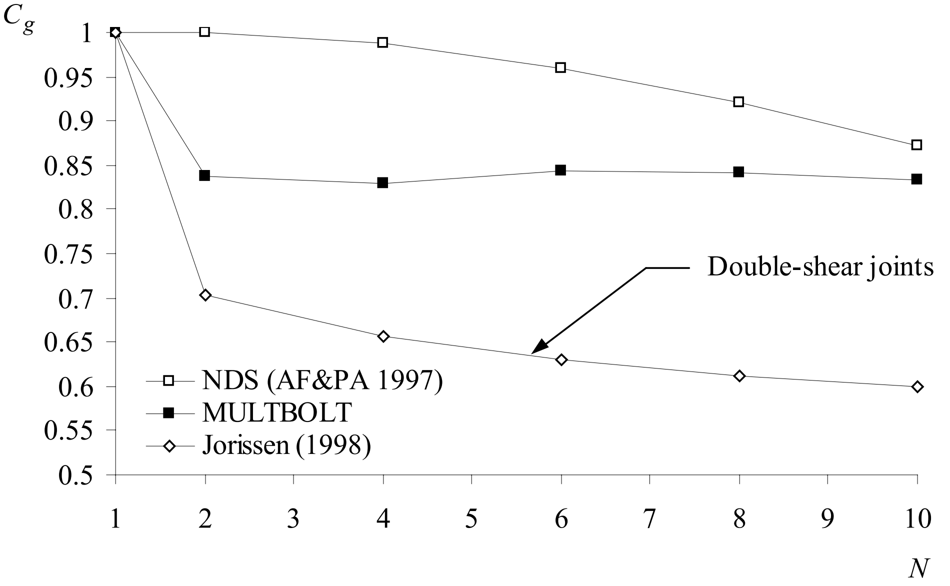

Figure 12.4: Group action factors predicted by the NDS, MULTBOLT, and Jorissen (1998). Jorissen tested three-member (double-shear) joints subjected to unidirectional displacement. Note, because Jorissen's equation is valid only for spacings larger than 5D, group action factors are computed for joints with 5D spacing. Results of joints containing 1, 2, 4, 6, 8, 10 bolts are

shown (bolt diameter D = 12.7 mm, southern pine members 38 x 140 mm^2, bolt spacing = 5D, end distance = 89 mm, modulus of elasticity for both members = 10.31 kN/mm^2)

12.2.2 Cyclic Displacing Function

In this study positive and negative load extrema were averaged to obtain absolute capacity. Positive maximum load was frequently greater than absolute negative maximum load. The reason was the displacement protocol used. Displacement amplitudes were always first increased on the upstroke (tension). Hence, the joint mostly failed in tension first, caused by splitting between bolts. Split segments between bolts reduced the joint load on the subsequent down stroke (compression). However, because of strength degradation, positive maximum load was not always greater than absolute negative maximum load.

Group action effects for cyclic displacement are similar to effects discussed for unidirectional displacement, but are more pronounced for cyclically stressed joints. The use of average capacity, rather than absolute maximum load, accounts for some of the differences. A further contribution is made by degradation on account of absorbed energy (Figure 12.6).

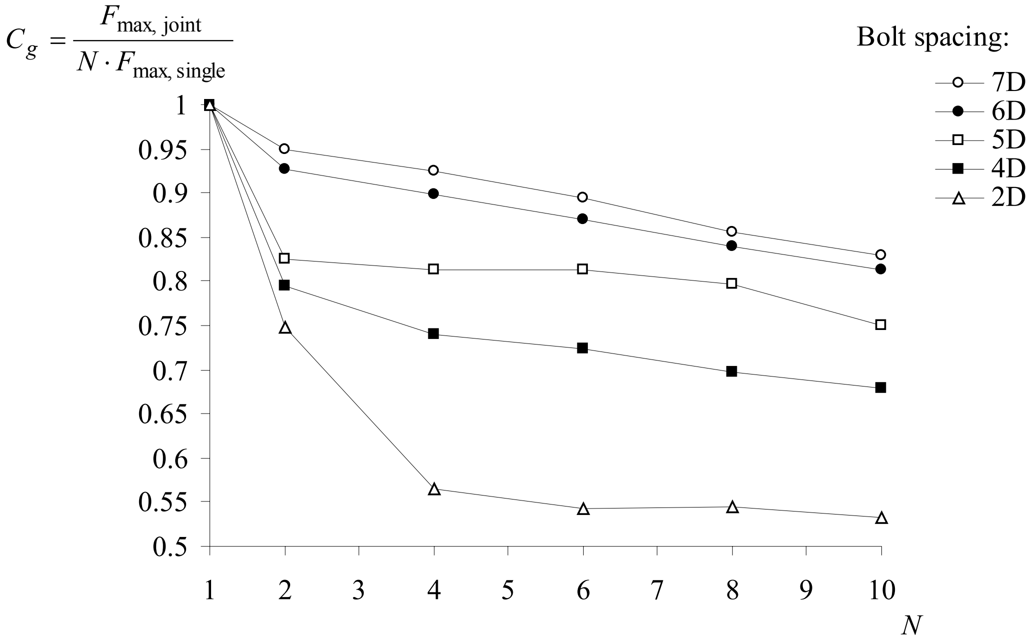

Figure 12.5: Group action effect of joints displaced cyclically. *N* denotes the number of bolts in a row. The y-axis represents the predicted group action factor C_g (relative capacity per bolt in a multiple-bolt joint compared with the capacity of a single-bolt joint). Results of joints containing 1, 2, 4, 6, 8, 10 bolts spaced 2D, 4D, 5D, 6D, 7D are shown (bolt diameter D = 12.7 mm, southern pine members 38 x 140 mm^2).

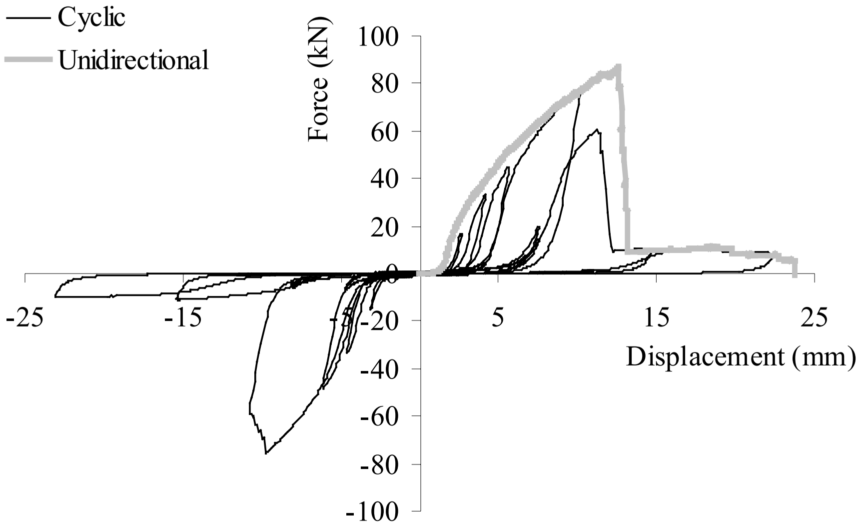

Figure 12.6: Example of different capacity because of varying energy absorption between cyclic and unidirectional displacing functions (10 bolt joint yielding in Mode II, bolt diameter D= 12.7 mm, southern pine 38 x 140 mm^2).

12.3 Effect of End Distance – No Stochastic Variation

The response was simulated for 2, 4, 6, 8, and 10 bolt joints yielding in Mode II with 2D, 4D, 5D, 6D, and 7D spacings (D = 12.7mm). On all joints, end distance was reduced to 4D. Except for the obvious case, single-bolt joints, MULTBOLT predicts that reduced end distance does not affect capacities of multiple-bolt joints with spacing ranging from 2D to 7D. Parallel-to-grain stresses approach zero in free-end segments (see Section 8.3.3). Moreover, superposition of perpendicular-to-grain stresses produces higher stresses within segments surrounding fasteners located in the middle (refer to Section 8.3.1). Failure, on the other hand, as predicted by the modified Tsai-Wu criterion, is influenced by the level of all stresses, which explains why the drop in end distance from 7D to 4D has a relatively low impact on results produced by MULTBOLT. When testing three-member, multiple-bolt joints (fastener diameter 12mm) subjected to unidirectional loading, Jorissen (1998) also did not find any significant change in capacity when decreasing end distance from 7D to 5D.

Table 12.1: Reduction of capacities if end distance is reduced from 8D to 4D (displacing function = cyclic, bolt diameter D = 12.7mm, southern pine 38 x 140 mm^2, modulus of elasticity for both members = 10.31 kN/mm^2)

Number of bolts	Spacing 2D	4D	5D	6D	7D
1	0.95	0.95	0.95	0.95	0.95
2	0.98	0.99	1.00	0.99	1.00
4	1.00	1.00	1.00	1.00	1.00
6	1.01	1.01	1.00	1.00	1.00
8	0.99	1.00	1.01	1.00	0.99
10	1.01	1.00	1.00	0.99	0.99

12.4 Material Property Variation

Figure 12.7 depicts a sample output of ten runs of MULTBOLT with material property variation turned on. Material properties were varied in two ways. The between-member parallel-to-grain E-modulus was varied using a COV of 32 percent (see Section 11.3.1). Also, the Markov model was turned on to account for spatial variation of MOE within a given member. A COV of 22 percent was input as main variation variable for the Markov model. The COV equals the average variation reported by Bodig and Jayne (1982) for small clear specimens of Longleaf pine, Slash pine, Loblolly pine, and Shortleaf pine, which belong to the Southern Pine species group. All other variables of the Markov model equaled the values established by Kline et al. (1985). As already alluded to in Chapter 9, the Markov model is used here only to investigate whether spatial material property variation has any significant effect on group action of multiple-bolt joints. Simulations were run using a Mode II-type joint containing 10 bolts in a row.

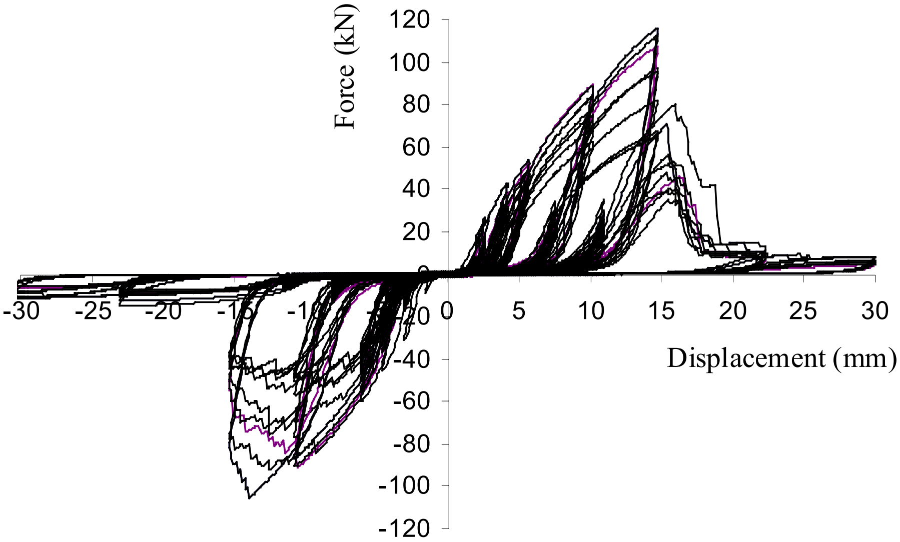

Figure 12.7: Sample plot of material property variation. Shown are the results of 10 MULTBOLT runs (10 bolt joint yielding in Mode II, bolt diameter D = 12.7 mm, spacing 7D, E modulus COV = 32 %, Markov model COV = 22%, southern pine 38 x 140 mm^2).

A COV of 32 percent of between-member material property variation and a COV of 22 percent of within-member variation induced a COV of less than 14 percent in maximum load of unidirectionally displaced specimens and less than 19 percent of cyclically displaced specimens. Gutshall (1994) observed a COV of 16.1 percent for the capacity of single-bolt joints (bolt diameter = 19mm) tested with southern pine members. A COV of 10.1 percent was obtained for the capacity of Mode II-type 5-bolt joints tested cyclically for this work.

Although all simulated group action factors were lower than predicted factors without material property variation, no significant influence of material property variation on group action could be detected for unidirectionally loaded specimens (Table 12.4). The higher effect of material property variation on the group action of multiple-bolt joints subjected to cyclic displacement is caused by several factors. For one, almost twice as much material influences the response because fasteners bear against segments left and right of them instead of segments located on only one side under unidirectional displacement. Furthermore, if failure occurs, say, on the upstroke in Segment X between two bolts close to the peak force reached during that cycle, then Segment X does not resist any forces during the subsequent down-stroke. The lowest negative force recorded for down-strokes is hence the peak force of the previous cycle, which may be, dependent on protocol used, significantly lower than the peak force that may have been reached in the current cycle. That explains in part, why variation and group action effect were higher.

For joints stressed cyclically, variability of capacity and group action tends to increase with increasing spacing. This could be attributed in part to the higher energy dissipation because joints fail at higher displacements (Figure 12.7). In addition, according to the weakest link theory, one would expect longer members to be weaker. However, that trend could not be observed on simulated joints displaced monotonically.

Table 12.2: Average group action factors of 30 MULTBOLT runs with simulated material property variation (within-member and between-member variation). Displacing function was **unidirectional**. Values are compared with group action factors obtained from MULTBOLT without simulated variation (10 bolt joint yielding in Mode II, bolt diameter D = 12.7 mm, southern pine 38 x 140 mm^2).

	Mean (kN)	COV (%)	Group Action	p-value (two-tailed t-test, one sample)
Spacing: 2D				
$F_{max,single}$	12.01	13.48		
$F_{max,10\text{-}bolt}$	75.38	6.38	0.63	0.654
No Variation			0.65	
Spacing: 4D				
$F_{max,single}$	12.01	13.48		
$F_{max,10\text{-}bolt}$	90.89	5.31	0.76	0.655
No Variation			0.78	
Spacing: 7D				
$F_{max,single}$	12.01	13.48		
$F_{max,10\text{-}bolt}$	112.25	6.10	0.93	0.733
No Variation			0.94	

Table 12.3: Average group action factors of 30 MULTBOLT runs with simulated material property variation (within-member and between-member variation). Displacing function was **cyclic**. Values are compared with group action factors obtained from MULTBOLT without simulated variation (10 bolt joint yielding in Mode II, bolt diameter D = 12.7 mm, southern pine 38 x 140 mm^2).

	Mean (kN)	COV (%)	Group Action	p-value (two-tailed t-test, one sample)
Spacing: 2D				
$F_{max,single}$	11.87	12.24		
$F_{max,10\text{-}bolt}$	58.50	13.13	0.49	
No Variation			0.53	0.033
Spacing: 4D				
$F_{max,single}$	11.87	12.24		
$F_{max,10\text{-}bolt}$	74.07	15.41	0.62	0.010
No Variation			0.68	
Spacing: 7D				
$F_{max,single}$	11.87	12.24		
$F_{max,10\text{-}bolt}$	83.76	18.27	0.71	0.001
No Variation			0.83	

12.5 Variation in Spacing and Slack

Chapter 9 detailed how tolerance in spacing leads to variability in initial slack. MULTBOLT includes slack variability by changing the initial conditions of the differential equations describing the modified hysteresis model. For example, if there is very little slack in positive displacement direction for a particular bolt, then the initial displacement at time $t = 0$ is close to hole oversize, which is + 1.6 mm. Notice that the initial displacement is positive. If the joint is displaced in positive direction, the resisted force of the bolt in question should quickly pick up if plotted against total joint displacement, since the bolt almost touches the hole boundary at its initial position. Along the same lines, the wood around the bolt in positive displacement direction fails at relatively small positive, total joint displacements, because the bolt is pressed into the material farther than other bolts with more initial slack in that direction. Based on the shift in initial conditions, MULTBOLT predicts correctly earlier failure of wood surrounding a bolt, if slack is less in that particular direction (Figure 12.8). The two fasteners that fail last in Figure 12.8, are the first and last bolt, which bear first against the greater end distance of Members 1 and 2, respectively, where total stresses perpendicular to the grain are lower (response simulation of joint with spacing of 4D and end distance of 7D is shown). In addition, fastener force picks up later (earlier), relative to total joint displacement, with increasing (decreasing) initial slack. Yet MULTBOLT mostly suppresses early load pick up at small displacements, which does not conform to reality (Figure 12.8). The suppression of early load pickup is caused by the new pinching function (Chapter 5). A reduction of the parameter ψ_0 to zero yields better results for small displacements but compromises hysteresis shape at larger displacements.

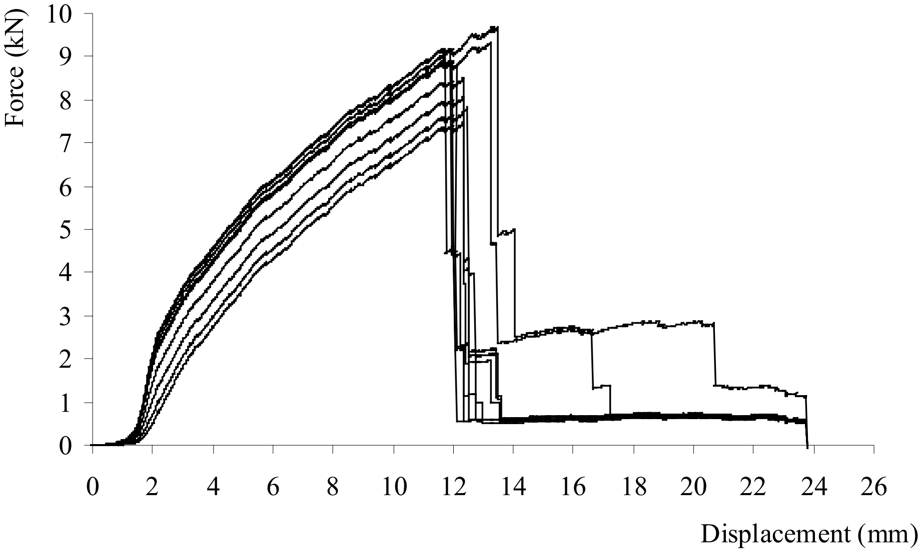

Figure 12.8: Load of individual fasteners versus total joint displacement for variable spacings within the joint. (10 bolt joint yielding in Mode II, bolt diameter D = 12.7 mm, southern pine 38 x 140 mm^2, spacing = 4D, spacing COV = 50%).

While all other variability was turned off, the COV for spacing variability simulations was chosen to be 12.5 percent, which is equivalent to the recommended hole tolerance of 1.6 mm for 12.7 mm diameter bolts. It is hard to imagine that real manufacturing tolerances would be greater than that. Comparisons are made using a 10-bolt joint yielding in Mode II.

Variations in spacing result in two effects. First, segments between bolts may be longer or shorter, and hence failure stresses may be reached at larger or smaller displacements, respectively. Second, variable spacing results in uneven slack distribution and individual bolts may be pressed farther, relative to total joint displacement, into the surrounding wood than others leading to earlier failure. Considering this, it may well be possible that the two effects sometimes offset each other.

Variations in spacing have a relatively small but significant effect on unidirectionally displaced specimens with fasteners spaced four bolt diameters apart and higher, because the relative change (i.e. the slope) of the load-displacement function is actually smallest before failure. A shallow slope implies relatively small changes in maximum load with changes in failure displacement resulting from varying slack. There appears to be a slightly higher effect of spacing variation for larger spacings. This is somewhat an artifact, however, because a constant COV was input to describe spacing variation, which results in higher absolute variations for larger spacings. The relatively small effect predicted by MULTBOLT for joints subjected to monotonic displacement agree with results obtained by Salenikovich et al. (1996) from single-shear joints and with data reported by Jorissen (1998) from double-shear joint tests.

Variations in slack should have no, or very little, effect on multiple-bolt joints under cyclic loading. To see this, consider Figure 12.9, where the bolt is located such that the slack in the direction of movement, as indicated by the two horizontal arrows, is very small. Hence the fastener is pressed into the surrounding wood at relatively small joint displacements and the resisted force picks up quickly, ultimately leading to early failure in that direction. Yet, if the direction of movement is reversed, the slack is much greater and failure comes at larger joint displacements. This is always the case because total slack (slack in positive direction plus slack in negative direction) must equal two times oversize. Thus, *average* cyclic capacity should not be affected by variations in slack. MULTBOLT correctly simulates this as portrayed in Table 12.5. No statistical significance could be detected for simulated specimens subjected to cyclic input and average capacities with slack variation are within 1 percent of average capacity without variation.

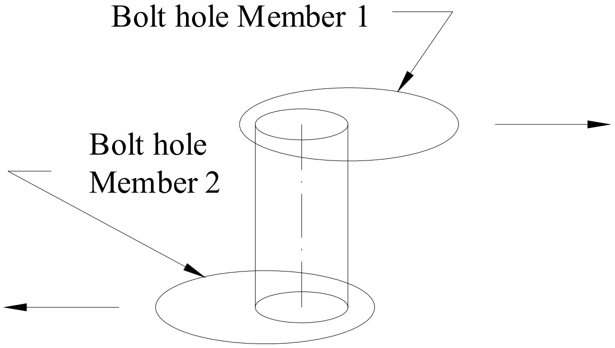

Figure 12.9: Example of slack variation of an individual fastener.

The real significance of manufacturing tolerances parallel to the direction of loading should be weighed carefully. If holes are drilled with a hand drill, as is often the case at construction sites, it is common practice to drill through both members at once, which effectively eliminates between-member spacing variation and hence total slack variation. However, this practice may still introduce significant variation of fastener spacing between fasteners. That is, since bolts can always be inserted by drilling through both members, two bolts may be spaced four diameters apart while others are located within three diameters of each other. In other words the potential spacing variation suddenly becomes much larger. This variation, on the other hand, substantially affects group action as shown in Section 12.2. Thus, while variation in slack may not be significant, *equal* variation in spacing per member definitely is.

Table 12.4: Average group action factors of ten MULTBOLT runs with simulated variation in fastener spacing, which directly determines variation in slack. Displacing function was **unidirectional**. Values are compared with group action factors obtained from MULTBOLT without simulated variation (10 bolt joint yielding in Mode II, bolt diameter D = 12.7 mm, southern pine 38 x 140 mm^2, spacing COV = 12.5%).

Spacing: 2D

	Mean (kN)	COV (%)	Group Action	p-value (two-tailed t-test, one sample)
$F_{max,single}$	11.29	4.09		
$F_{max,10\text{-}bolt}$	70.84	2.38	0.63	0.146
No Variation			0.65	
Spacing: 4D				
$F_{max,single}$	11.29	4.09		
$F_{max,10\text{-}bolt}$	83.96	2.47	0.75	0.035
No Variation			0.78	
Spacing: 7D				
$F_{max,single}$	11.29	4.09		
$F_{max,10\text{-}bolt}$	100.36	3.05	0.89	0.005
No Variation			0.94	

Table 12.5: Average group action factors of ten MULTBOLT runs with simulated variation in fastener spacing, which directly determines variation in slack. Displacing function was **cyclic**. Values are compared with group action factors obtained from MULTBOLT without simulated variation (10 bolt joint yielding in Mode II, bolt diameter D = 12.7 mm, southern pine 38 x 140 mm^2, spacing COV = 12.5%).

	Mean (kN)	COV (%)	Group Action	p-value (two-tailed t-test, one sample)
Spacing: 2D				
$F_{\mathrm{max,single}}$	11.30	2.64		
$F_{\mathrm{max,10\text{-}bolt}}$	59.97	1.09	0.53	0.862
No Variation			0.53	
Spacing: 4D				
$F_{\mathrm{max,single}}$	11.30	2.64		
$F_{\mathrm{max,10\text{-}bolt}}$	76.47	1.82	0.68	0.933
No Variation			0.68	
Spacing: 7D				
$F_{\mathrm{max,single}}$	11.30	2.64		
$F_{\mathrm{max,10\text{-}bolt}}$	92.04	1.25	0.82	0.114
No Variation			0.83	

12.6 Dynamic Displacing Function

Although predictions for dynamic displacing functions have not been validated, results are shown to demonstrate that MULTBOLT does handle random input functions. A scaled version of the 1995 Kobe earthquake record (JMA Station East-West, downloadable free of charge from: http://www.eresonant.com/pages/motions/motions.html#Anchor-194-46249) was used to trigger inertia forces (Figure 12.10). Scaling was necessary to obtain displacements within the sustainable range of the joint. It is assumed that the joint is connected to a lumped mass of 10,000kg, which translates into significant forces caused by acceleration.

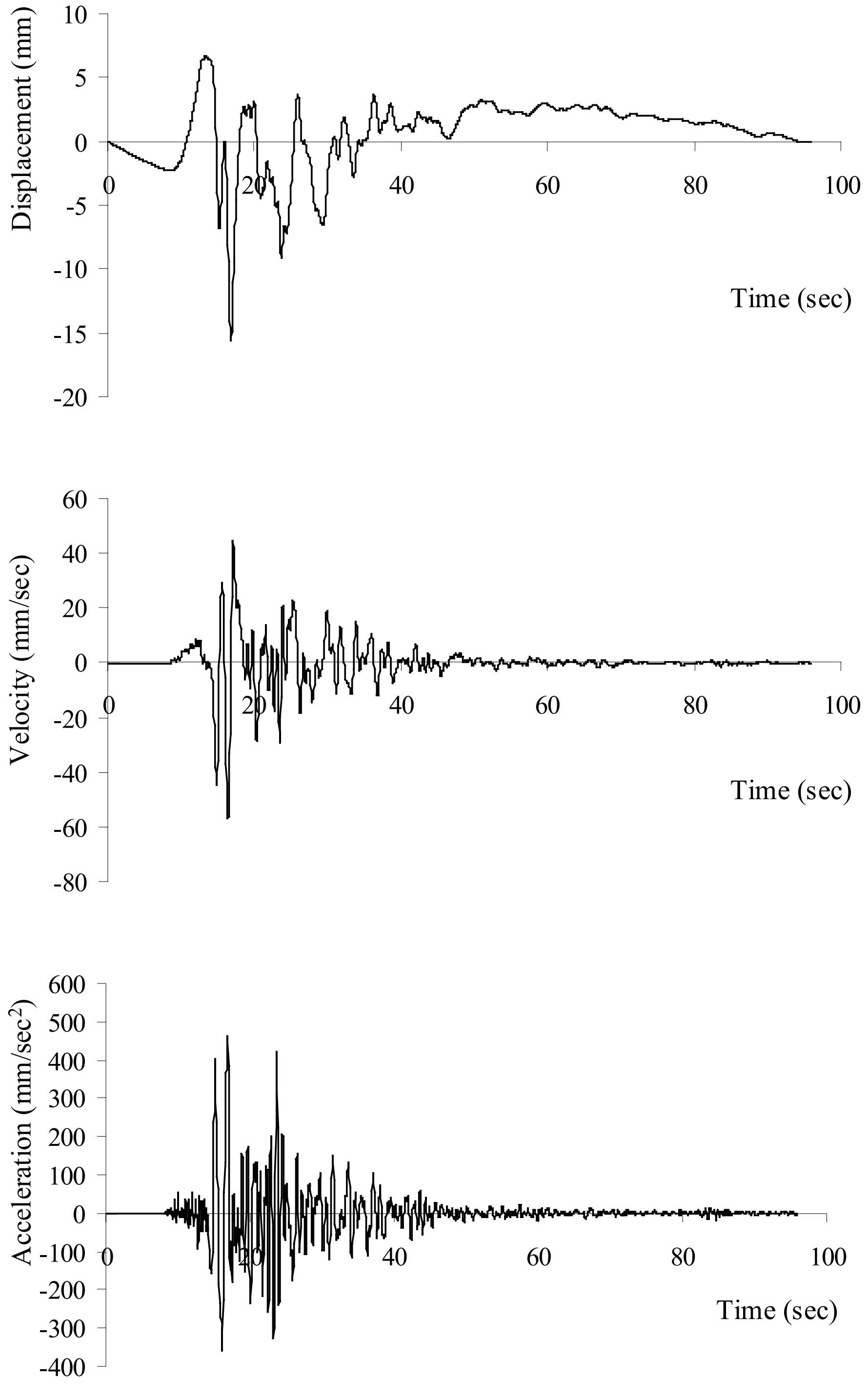

Figure 12.10: Scaled version of the 1995 Kobe earthquake record (JMA Station – East West) used as input for MULTBOLT.

Response predictions by MULTBOLT are depicted in Figure 12.11. It should be noted that MULTBOLT correctly predicts significantly higher viscous damping forces associated with higher velocities, which can be seen by the considerable forces at and near zero displacement. Furthermore, the graph depicts the significance of slack and asymmetric slack growth, which should conform to reality because slack and slack growth was modeled to be influenced by displacement level rather than absorbed energy. However, extended validation will shed more light on that issue.

It is acknowledged here that the use of an earthquake record to predict joint performance is somewhat an academic exercise and really serves to demonstrate that MULTBOLT is not limited to slowly varying input functions. Joints in structures are subject to displacements imposed upon by the structural environment. In other words, displacements depend on stiffness and displacements of other members brought about by the overall deformation of the structure due to earthquake ground motions. Thus, the displacing function of a structural joint may have no relation to the ground motion triggered by earthquakes.

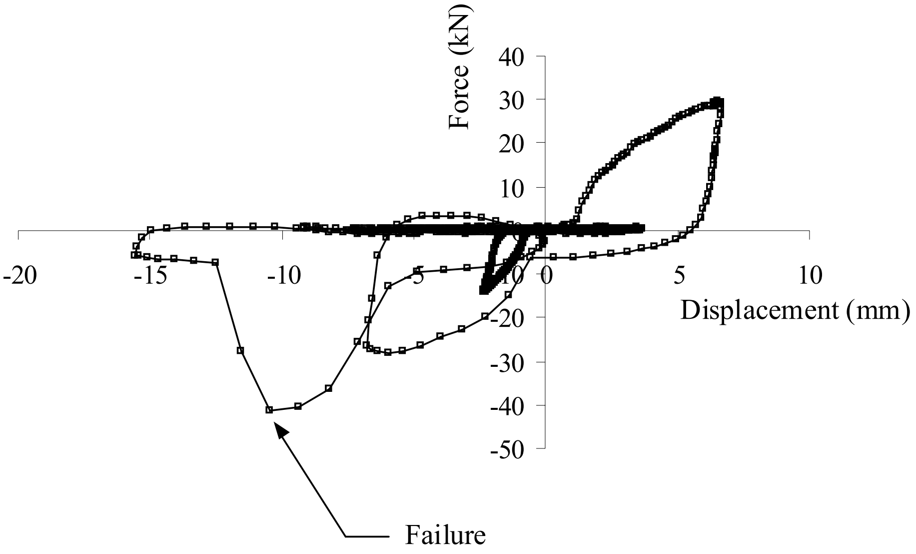

Figure 12.11: Simulated response to the scaled-down version of the 1995 Kobe earthquake record (3 bolt joint yielding in Mode II, bolt diameter D = 12.7 mm, southern pine 38 x 140 mm^2).