# DAMPING AND STIFFNESS OF NAILED JOINTS: RESPONSE TO DRYING[1]

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## ABSTRACT

On the West Coast, Douglas-fir components are usually assembled into structures in green or semi-seasoned condition, and as they dry during initial service life, gaps often develop between the contact surfaces of the wood joints. The effect of such gaps on joint damping and slip variables was evaluated using cyclic-load tests on single-nail joints constructed with Douglas-fir stud and plywood sections. The stud sections were exposed to various changes in moisture content before and after joint assembly.

Observed damping ratios and slip moduli were significantly smaller for joints with gaps (assembled green and tested dry) than for those without gaps (assembled and tested at the same moisture content). Increases in load magnitude decreased slip modulus and increased damping ratio of joints with interlayer gaps, but decreased damping ratio of those without such gaps. Variations in surface roughness of the stud (from machining) affected neither damping nor stiffness significantly.

*Keywords:* Damping, stiffness, slip, energy absorption, energy capacity, nailed joints, wood, plywood, testing, moisture content.

## INTRODUCTION

Damping is the ability of a structure to dissipate energy during vibration. The two sources of damping in nailed wood joints are material damping within the wood and slip or frictional damping along contact interfaces. In the past, slip damping has not been considered a factor in the design of wood buildings (Earles and Philpot 1967). However, if the total stress in a structural member is maintained below working stress, material damping is small and the total energy dissipation in the structure is dominated by slip damping (Keneta 1958; Yeh et al. 1970; Polensek 1975). Design methods currently being developed will incorporate slip damping into the dynamic analysis of components and component connections in wood buildings (Atherton et al. 1980).

Stiffness (resistance to deformation) is measured by slip or deflection and is the most significant design parameter that affects building serviceability. Antonides et al. (1979) presented an extensive review of the variables influencing nailed wood joints. Loferski and Polensek (1982) and Foschi and Bonac (1977) presented information on the nonlinear characteristics of load-deflection curves of nailed joints, and such relationships must be considered if accurate prediction of the responses of wood buildings to overloads is to be achieved.

Static and dynamic loading have generally been the methods employed in evaluation of damping and stiffness in wood joints and structures. Young and Medearis (1962) subjected plywood diaphragms to static cyclic loading to determine the importance of damping in earthquake resistance, and these tests led

them to adopt the concept of equivalent viscous damping for evaluating damping ratio. They then tested to failure 8- by 8-ft shear-wall specimens constructed of 2- by 4-in. framing sheathed with plywood, and found that the overall damping ratio of the panels was about 0.10. Polensek (1975) found that damping ratios of nailed wood-joist floors ranged from 0.04 to 0.06 when tested in bending and from 0.07 to 0.11 when tested as diaphragms. Polensek (1976) also tested eleven 20- by 60-ft roof diaphragms under free vibration, and found that their damping ratios ranged from 0.03 to 0.32.

Damping and stiffness of nailed joints in structural components have been studied by static cyclic loading of one-nail specimens representing joints between wood and sheathing plywood, as was done in this study. Atherton et al. (1980) tested joints of wood and plywood under four fully reversed load cycles at five magnitudes, and found that load magnitude greatly affected slip modulus and energy absorption. Keneta (1958) studied damping and stiffness of wood joints and concluded that, if loading conditions are known, load-deflection characteristics of single-nail joints could be used to determine those of composite framed panels.

Attempts have been made to model damping mechanisms in wood joints. Using static loading of nailed and glued I-beams made of lumber and plywood, Yeh (1970) developed a theoretical model to predict overall damping ratios of lumber and plywood T-beams, but correlation between model predictions and experimental results was poor.

The present study used static cyclic loading to determine the effect of changes in lumber moisture content (MC) on damping and slip variables of typical nailed wood joints. The type of joint studied is frequently used in housing construction in the United States, and consists of $^{19}/_{32}$-in. sheathing plywood fastened to a Douglas-fir 2-by-4 stud with a single 6d nail.

## MATERIALS AND METHODS

### Materials

Twenty-five Douglas-fir studs of nominal 2- by 4-inch size were visually selected for straightness of grain and freedom from defects. The specific-gravity histogram of these studs matched that of a representative sample of Douglas-fir studs. A 12-inch-long section was cut from each stud.

Three 4- by 8-foot sheets of sheathing-grade, 5-ply, $^{19}/_{32}$-inch Douglas-fir plywood were purchased from a local lumberyard and cut into 4- by 12-inch sections with the face grain parallel to the 12-inch side. Fifty such sections were visually selected for freedom from defects.

Galvanized, smooth, 6d box nails (average diameter 0.104 in.) were used in construction of all joints tested.

### Construction of joints

All joints tested in this study were constructed in the following manner: a plywood section was positioned against the narrow edge of a stud section so that the plywood contacted 4 in. of the stud's length. One nail was driven through the center of the contact area (Fig. 1) until the top of the nail head was in the plane of the plywood surface.
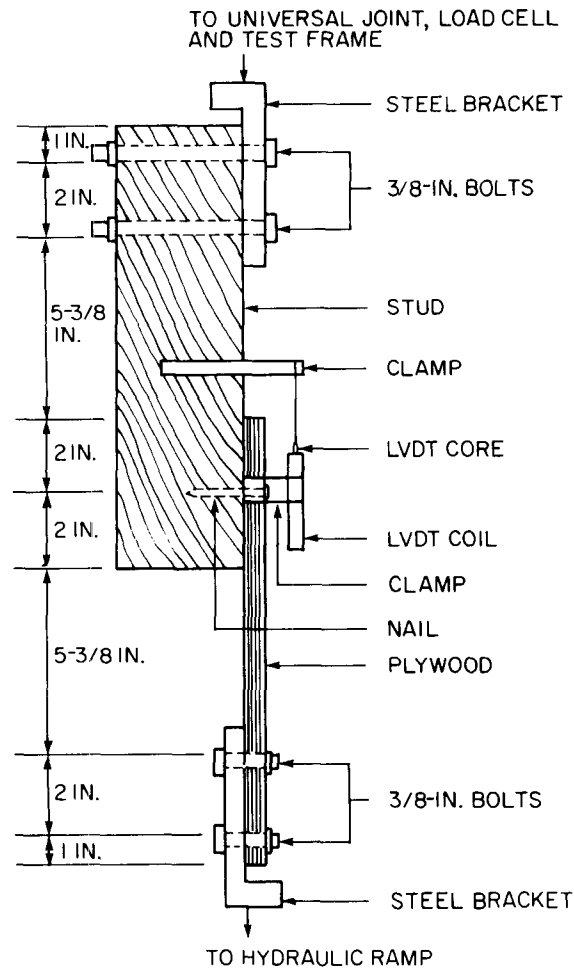
FIG. 1.   One-nail joint specimen ready for testing.

Stud and plywood sections were reused in construction of joints for subsequent rounds of testing. Therefore, at the end of each round of testing (except round 3), tested joints were dismantled. A 1-inch section was cut from the previously joined end of each stud and plywood section, and new joints were constructed.

### Testing sequence

Five rounds of tests were performed, one for each stud moisture treatment. Half of the joints tested in each round were constructed on the rough edges of the studs, the other half on the smooth edges. Before any joints were constructed, all stud and plywood sections were allowed to equilibrate in a conditioning room to approximately 12% MC, which was considered "dry" for the purposes of this study. Moisture content of plywood sections did not change during the testing procedure.

In round 1 (12% NO GAP), 25 single-joint specimens were constructed on the smooth edges of the studs and tested. These were then dismantled, new joints
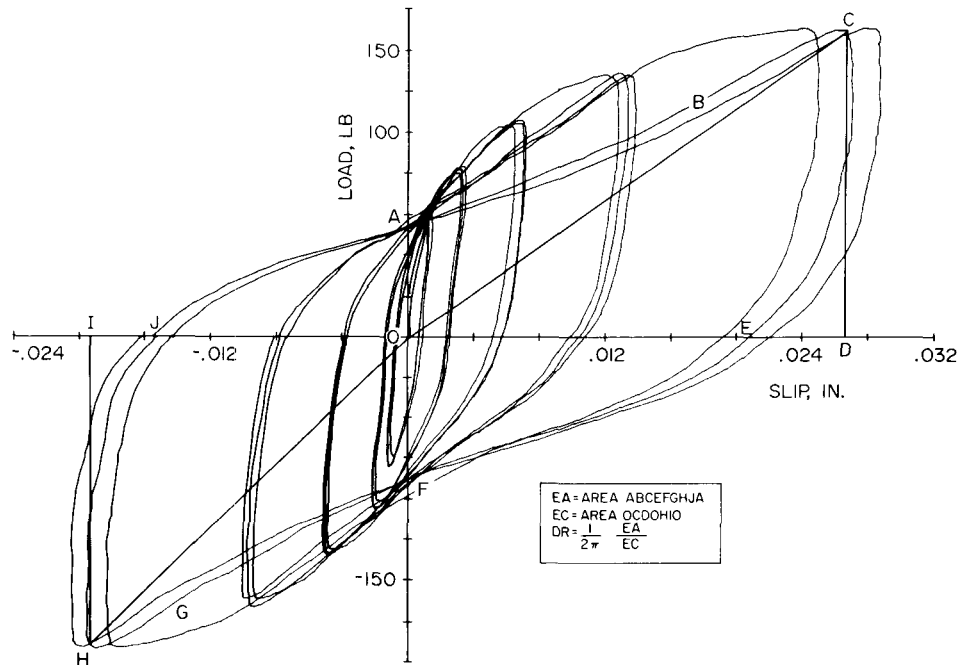
FIG. 2.    Typical L-S traces for samples without gap.

were constructed on the rough edges of the same studs, and the tests were repeated. All 50 joints in round 1 were constructed and tested dry.

In round 2 (GREEN), the same construction and testing procedures were followed, except that the studs from round 1 were pretreated in a pressure tank to raise their MCs to the fiber saturation point (approximately 28%). All joints in round 2 were constructed and tested in this saturated condition.

In round 3 (18% GAP), 25 two-joint specimens (plywood sections attached to both the smooth and the rough edge of each stud) were assembled using the green studs from round 2. These specimens were then subjected to drying, and when the studs had reached approximately 18% MC, 13 of the smooth-edge joints and 12 of the rough-edge joints were tested.

In round 4 (12% GAP), the two-joint specimens constructed for round 3 were further dried to approximately 12% MC, and the remaining untested 12 smooth-edge and 13 rough-edge joints were tested.

In round 5 (12% CYCLED), the studs from rounds 1 through 4, having gone through a cycle from dry to green to dry, were treated as in round 1; they were assembled into single-joint specimens, first on the smooth and then on the rough edges of the studs, and tested in each configuration. The purpose of this round was to evaluate the effect of stud moisture cycling on the slip and damping properties of joints.

### Testing procedure

The stud and plywood sections of the joint being tested were bolted to steel brackets in such a manner that bending moment along the contact surfaces of the

Table 1. *Significant effects of moisture content, load level, and interlayer roughness on slip and damping.*

| | Slip | | Damping | | |
|---|---|---|---|---|---|
| Source of variation | Positive half-loops | Negative half-loops | Energy absorption (EA) | Energy capacity (EC) | Damping ratio |
| **Main effects** | | | | | |
| Moisture content (MC) | 0.001* | 0.001* | 0.001* | 0.001* | 0.001* |
| Load level (LL) | 0.001* | 0.001* | 0.001* | 0.001* | 0.001* |
| Interlayer roughness (ROU) | 0.009* | 0.894 | 0.099 | 0.052 | 0.001* |
| **Interactions** | | | | | |
| MC × LL | 0.001* | 0.001* | 0.001* | 0.001* | 0.001* |
| MC × ROU | 0.565 | 0.001* | 0.652 | 0.560 | 0.001* |
| LL × ROU | 0.068 | 0.998 | 0.400 | 0.185 | 0.827 |
| MC × LL × ROU | 0.971 | 0.001* | 0.825 | 0.594 | 0.999 |

* Significant at the 1% level of critical significance.

joint would be minimized under load (Fig. 1). The load cell was connected to an X-Y recorder, and provided the signal by which the applied load was monitored. Slip was recorded with a linear variable-differential transformer (LVDT) that supplied a signal to the X-Y recorder. Load cell capacity was 1,000 lb; LVDT range was 0.1 in.

All joints were subjected to three fully reversed cycles at each of five load levels: 70, 100, 130, 160, and 190 lb. The loading rate used (1.5 in./min) is about 10 times higher than that recommended by ASTM (1979). This rate was chosen to reflect current trends in wood testing, and also to reduce testing time.

## Data analysis

The load-slip (L-S) traces (Fig. 2) of the first and third cycles at each load level were not included in the data analyses because of their association with the previous (lower) and next (higher) load levels, respectively. All second-cycle L-S traces were digitized by computer to facilitate evaluation of damping variables and slip.

The damping variables analyzed were those used by Young and Medearis (1962): total energy absorption per cycle (EA), total energy capacity per cycle (EC), and damping ratio (DR). The slip values considered were the extreme values for each load level (e.g., those identified in Fig. 2 as OD and OI for the fifth load level). At the 190-lb load level, slip magnitude occasionally exceeded the range of the LVDT. EA, EC, and DR related to these out-of-range slip values were used in the analyses to show trends at high loads. Secant slip moduli, which characterize joint stiffness, were derived by dividing these slip values into the corresponding load magnitudes. (Hereinafter, the term "slip modulus" refers to the secant slip modulus just described.)

Effects of MC, load level, and interlayer roughness on slip, EA, EC, and DR were evaluated statistically using a three-factor analysis of variance (ANOVA). The statistic used to detect significant relations was the level-of-variance ratio, F, defined as the ratio of the variance between samples to the variance within samples. The level of critical significance was set at 1%.
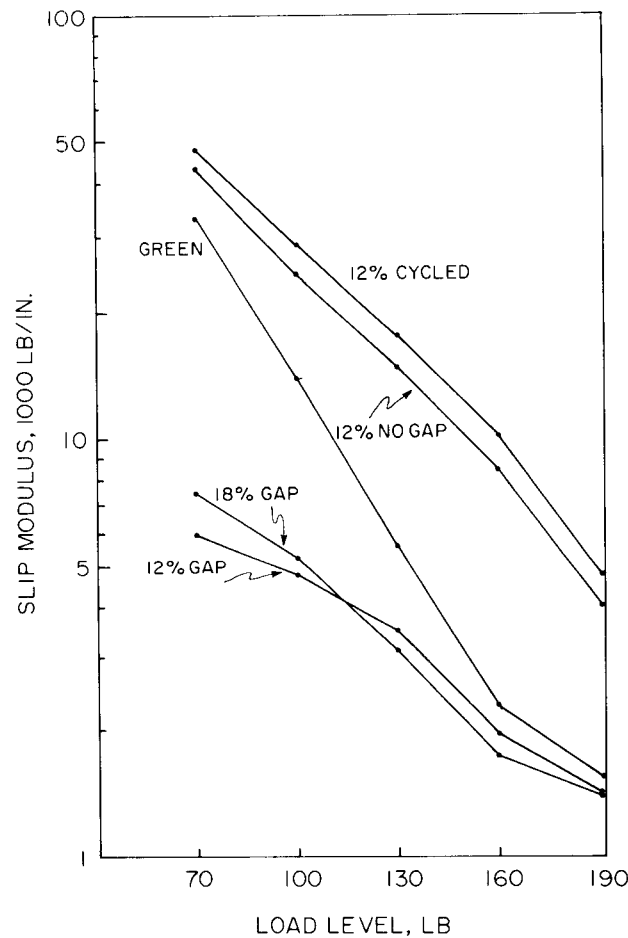
FIG. 3.    Relationship between load and slip modulus for the five MC treatments investigated.

## RESULTS AND DISCUSSION

The L-S traces in Fig. 2 can be visualized as a set of hysteresis loops. Most traces are symmetrical with respect to the slip axis, but some are nonsymmetrical in that their axes of zero slip are translated along the slip axis from that of the initial half-loop. Note that the damping variables EA, EC, and DR are defined in terms of the L-S traces themselves.

Table 1 identifies the significant effects of MC, load level, and interlayer roughness on slip, EA, EC, and DR. To enhance test sensitivity, the analysis of variance for slip was conducted separately for positive and negative half-loops, even though the slip moduli are essentially derived from averages of the half-loop values. Because the F statistic for EA indicated a significant two-way interaction between MC and load level (Table 1), analysis of the effect of MC on EA and EC was conducted at each load level, whereas analysis of the effect of load level on EA and EC was conducted individually for each MC treatment.

TABLE 2. *Results of linear regression analysis defining the effect of load level and moisture content on joint properties.*

| Dependent variable (Y*) | Matched samples** | Regression model: Y = A + (B)(LL) + (C)(CMC) | | | |
|---|---|---|---|---|---|
| | | A | B | C | R² |
| LOG(AS) | | 0.8292 | 0.01500 | −0.0209 | 0.91459 |
| LOG(EA) | 2, 3, 4 | 0.6661 | 0.01577 | −0.0442 | 0.90927 |
| LOG(EC) | | 1.0037 | 0.01592 | −0.02566 | 0.91001 |
| LOG(AS) | | −0.2583 | 0.01374 | 0.02208 | 0.91466 |
| LOG(EA) | 1, 2, 5 | −0.2433 | 0.01566 | 0.02794 | 0.90246 |
| LOG(EC) | | −0.5654 | 0.01655 | 0.02648 | 0.90206 |
| DR | 3, 4 | 788.9 | 34.17 | 1.63 | 0.09806 |
| DR | 1, 2, 5 | 3,728.6 | −5.51 | 0 | 0.09862 |

* AS = average slip (×10,000) per loop; EA = total energy absorption (×100) per loop; EC = total energy capacity (×100) per loop; and DR = damping ratio (×10,000).
** Sample type: 1 = 12% NO GAP (calculated moisture content [CMC] = 12.6%); 2 = GREEN (CMC = 28%); 3 = 18% GAP (CMC = 18%); 4 = 12% GAP (CMC = 13.6%); and 5 = 12% CYCLING (CMC = 14.6%).

## Effect of MC

Three combinations of treatments were involved in the investigation of moisture effects: 12% NO GAP and 12% CYCLED treatments for the effect of moisture cycling; 12% NO GAP and GREEN treatments for the effect of water saturation; and GREEN, 18% GAP, and 12% GAP treatments for the effect of drying.

The effect of MC on slip modulus was examined first. Moisture cycling caused slip moduli to be greater in 12% CYCLED joints than in 12% NO GAP joints (Fig. 3). This resulted from the difference in MC caused by moisture cycling (see footnotes, Table 2, for actual calculated MC), which produced tighter interlayer contact in 12% CYCLED joints. Similarly, slip moduli were smaller in GREEN joints than in 12% NO GAP joints, probably because wood cell walls are weaker when water-saturated. As expected, all joints with interlayer gap exhibited lower slip moduli than did joints without gap.

The results showed that moisture cycling of lumber before construction of joints (12% CYCLED) somewhat increases EA over that in joints without moisture cycling (12% NO GAP) (Fig. 4). Water saturation of lumber caused larger EA in the GREEN treatment than in the 12% NO GAP treatment. Furthermore, EA values were shown to depend not only on the shapes of the L-S traces, but also on load magnitude. For example, at loads of 70 and 100 lb, the 12% GAP and 18% GAP treatments had larger EA than did the GREEN treatment, primarily because the former had greater gap-induced slip and, therefore, larger areas under the L-S traces. However, at loads above 100 lb, EA was larger in the GREEN treatment than in the 12% GAP and 18% GAP treatments, even though slip moduli at loads above 100 lb were about the same for all three treatments. This disparity arose because of friction in the GREEN joints, which were without gap.

The results also showed EC to be smaller in the 12% CYCLED joints than in the 12% NO GAP joints (Fig. 5) because of the tighter interlayer caused by moisture cycling. Moreover, water saturation of the studs in GREEN joints caused their EC to be much greater than that of 12% NO GAP joints, largely because of cell-wall weakness in the GREEN treatment. In contrast with EA, EC values were dependent not on the shape of the L-S traces but on the magnitude of the maximum
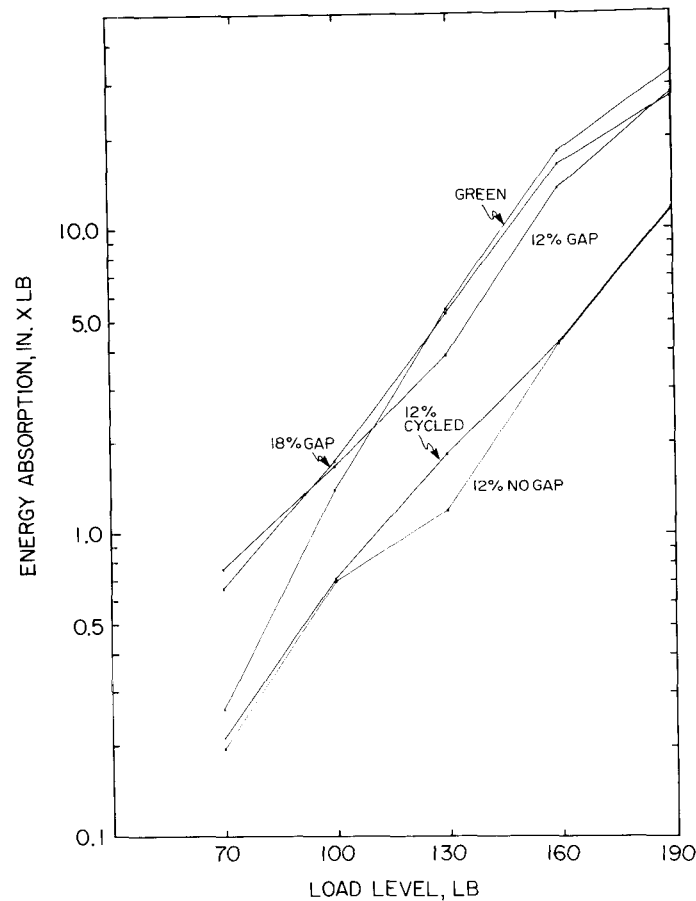
FIG. 4. Relationship between load and total energy absorption per load cycle for the five MC treatments investigated.

slip and load at each load level. Thus, 12% GAP and 18% GAP joints had the largest EC's because drying-initiated gap decreased their stiffness, which in turn increased the areas of the two triangles OCDO and OHIO (Fig. 2).

The results showed that DR is directly related to interlayer friction: joints without gap exhibited larger DR than did those with gap (Fig. 6). Thus, DR was larger in 12% CYCLED joints than in 12% NO GAP joints because the former had a tighter interlayer; DR in GREEN joints was intermediate between those of the other treatments without gap; and joints with gap had the lowest DR because of their lack of interlayer friction.

## *Effect of load level*

The consequence of changing load level can be evaluated by examining Figs. 3, 4, and 5. As expected, slip modulus decreased and EA and EC increased with increasing load. At load levels of 70 and 100 lb, these three variables were similar among GREEN, 12% NO GAP, and 12% CYCLED treatments; however, at 130, 160, and 190 lb, these values for the GREEN treatment approached those for the
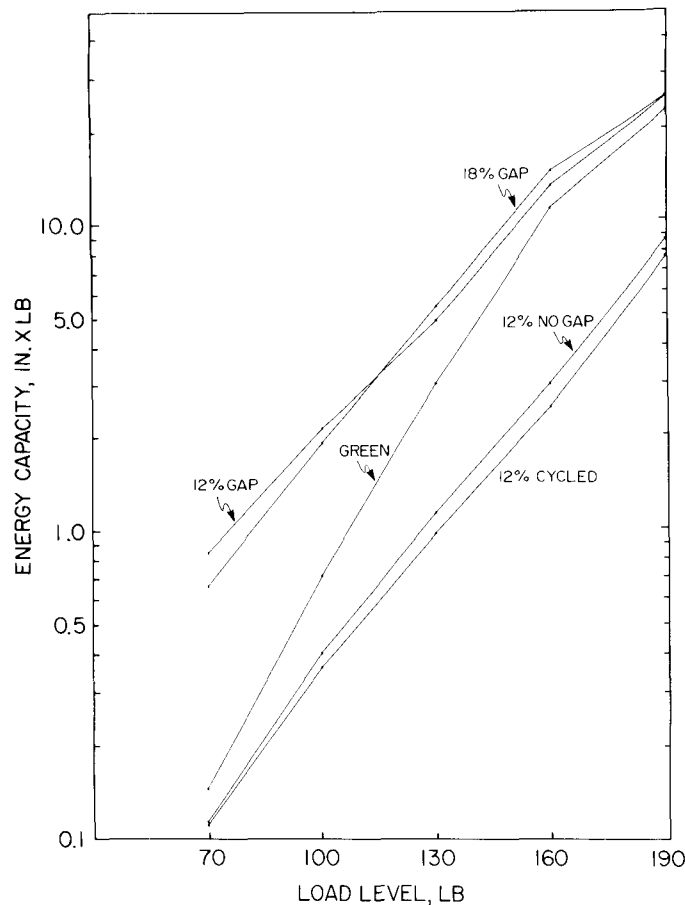
FIG. 5.  Relationship between load and total energy capacity per load cycle for the five MC treatments investigated.

two treatments with gap. This pattern can be explained by the presence of interlayer friction in joints without gap at small loads. Similar reasoning suggests that the moisture-related weakening of cell walls in the GREEN treatment produced greater slip at high load.

Figure 6 illustrates the relationship between DR and load level for all five treatments. Generally, at higher load levels DR of joints without gap decreased and that of joints with gap increased as load increased. The most likely explanation is that 1) plywood sections in joints without gap became slightly separated from the studs at high load, reducing interlayer contact and, therefore, friction and damping; and 2) drying-initiated gap was closed somewhat by nail and wood deformation as load increased, forming a partial contact interface and thereby increasing friction and damping.

Linear regression analysis, which quantified the relationships among Figs. 3 to 6, revealed several significant effects (Table 2). For slip modulus, EA, and EC, the coefficient of determination ($R^2$) was consistently above 0.7. For DR, however,
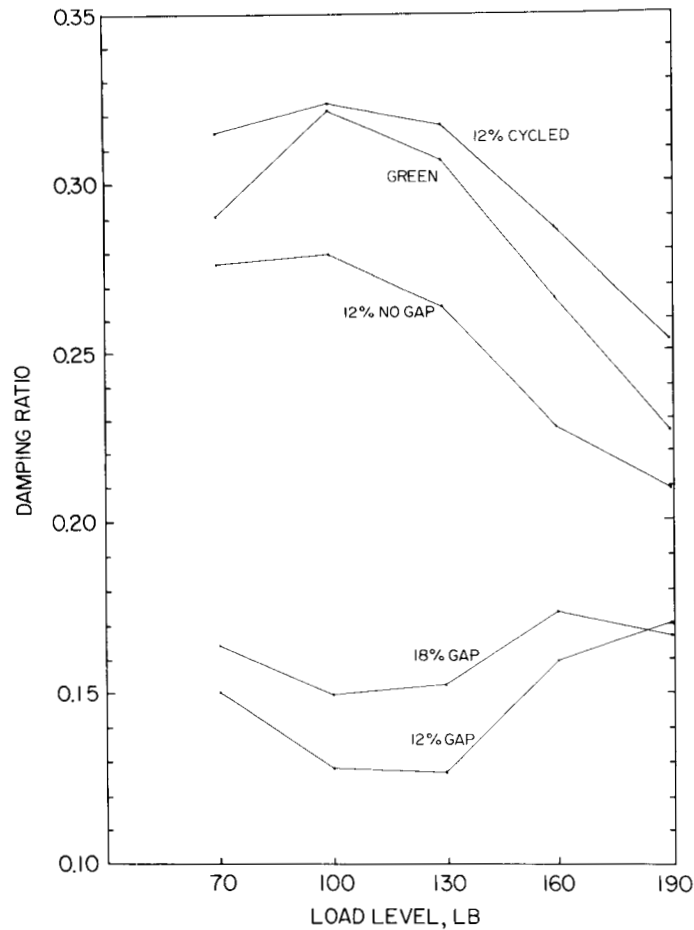
FIG. 6. Relationship between load and damping ratio for the five MC treatments investigated.

$R^2$ values were smaller, indicating no strong correlations among DR, load level, and MC.

### Effect of stud roughness

Analysis of the effects of stud roughness was restricted to treatments without gap, because gap physically eliminates interlayer friction. A one-factor ANOVA of the treatments without gap, conducted at each load level, revealed no significant effect of interlayer roughness on any variable except DR at the 5% level of critical significance. Means for DR were somewhat larger for joints with smooth than for those with rough interface, probably because of reduced contact area in the latter.

### CONCLUSION

The results of this study show that damping ratio decreases with increasing load for joints that are constructed and tested in the same moisture condition, and that it slightly increases with increasing load for joints that are constructed green

and tested dry. Observed damping ratios for joints with smooth interface were about 6% larger than those for joints with rough interface. However, no significant effect of interlayer roughness on damping ratio was detected.

The results also show that, as expected, slip moduli decrease with increased load level, and that slip moduli at maximum load are smaller for joints with interlayer gap than for those without gap. No significant effect of interlayer roughness on slip modulus was observed.

The most important results pertain to the reduction in damping ratio of joints constructed with green lumber and then dried to the moisture content expected during the normal service life of wood structures. Joints in this study had a mean damping ratio of approximately 0.28 when assembled and tested with green lumber, but this decreased to approximately 0.15 when the joints were dried to 12% MC. Because most previous tests of structural wood joints ignore this effect of drying, design values based on testing of unseasoned specimens can overestimate by a factor of two. Further research is needed to determine correction factors for changes in moisture content of commonly used wood joints.

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