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Effect of Moisture Cycling On Mechanical Response of Metal-Plate Connector Joints With and Without an Adhesive Interface

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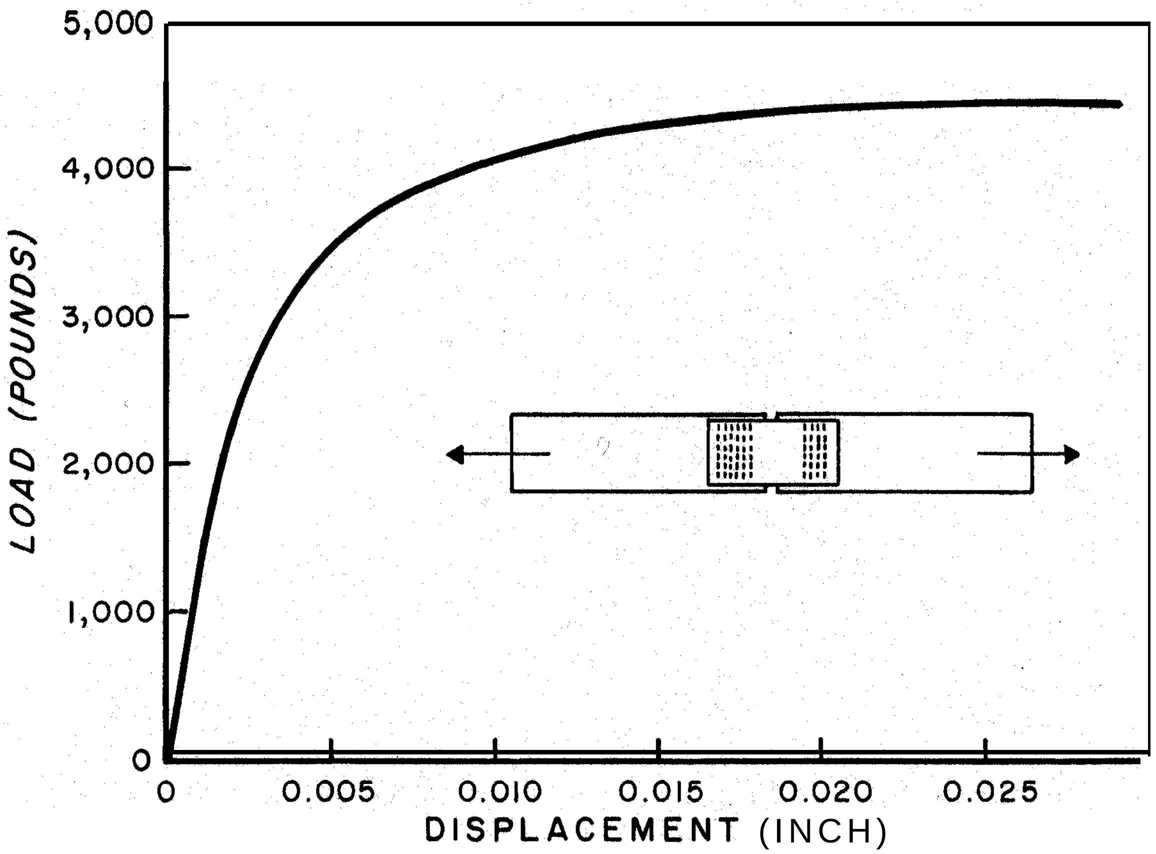

SUMMARY

Wood trusses are frequently located in light-frame structures where they are subjected to significant shifts in moisture conditions. However, little is known about the effects of moisture cycling of the wood members on the mechanical behavior of metal-plate connector (MPC) joints. Thus, the primary objective of this study was to quantify the effect of wood moisture content fluctuations on MPC joint behavior. A secondary objective was to investigate maintaining interfacial integrity between the metal-plate teeth and wood by applying an epoxy adhesive at the interface and noting the changes in mechanical performance of MPC joints.

Results of this study indicate that moisture cycling significantly affects the mechanical performance of MPC joints. Some of the decline in mechanical performance could be attributable to plate "backout." It was shown that in addition to a decrease in mechanical performance, moisture-cycled specimens probably have an altered stress transfer mechanism as exhibited by load-slip traces. Initial stiffness of the load-slip traces is most drastically affected by moisture cycling, but ultimate load and load-at-0.015~inch-slip were also affected. Addition of an adhesive interface between the teeth and wood appears to increase the mechanical performance of MPC joints. However, the apparent increase in mechanical performance could not be quantified due to the lack of identically matched specimens. The degrade ofultimate load and load-at-0.015-inch-slip of MPC joints with an adhesive interface was similar to that of standard MPC joints. Initial stiffness of MPC joints with an adhesive interface degraded more rapidly than standard MPC joints, probably due to weakening of the adhesion between the teeth and wood. Addition of an adhesive to the tooth-wood interface resulted in less variability of mechanical properties when compared to standard MPC joints, with this variability remaining constant regardless of number and severity of moisture cycles.

Effect of Moisture Cycling on Mechanical Response of Metal-Plate Connector Joints With and Without an Adhesive Interface

L.H. Groom

INTRODUCTION

The fundamental purpose of a truss system in construction is to transfer applied loads to the structure framework and eventually the foundation, with some of the load being absorbed in the truss system through internal friction and damping. The trend in truss design in the last 15 years has been to reduce the amount of material necessary to resist the design loads. This increase in efficiency has led to higher stresses in the truss members. However, restrictions placed on old-growth timber stands and an increase in plantation-grown timber will result in a timber base with markedly lower mechanical properties. This paradox of increased demand for superior lumber with a decreased availability of a quality-product lumber supply will lead to research aimed at changing current design values and practices (Galligan 1990).

In most cases, truss performance is a reflection of the properties of the joints (Wilkinson 1984). Failure of truss systems occurs primarily at the joints due to stress concentrations, whereas large deflections in truss systems are generally the result of small joint displacements (Reardon 1971). Thus, evaluation of truss performance must begin by understanding the mechanical behavior of metal-plate connector (MPC) joints.

Predictive models have been developed for the static structural behavior of MPC joints by various researchers (Crovella and Gebremedhin 1990, Foschi 1977, Groom 1988, Triche and Suddarth 1988). However, these models concentrate on the fundamental mechanisms of stress transfer and ignore secondary variables such as moisture cycling. Moisture cycling is critical for truss systems because trusses are often found in the most environmentally extreme areas: attics and basements. Joist and rafter moisture content (MC) in these environments has been shown to fluctuate seasonally by anywhere from 10 percent (Cunningham 1984, Duff 1978) to as much as 18 percent (Cleary 1984, Cunningham 1983, Sherwood 1985). This type of moisture cycling can affect truss performance. Unfortunately, the effect of moisture cycling has not been quantified. As a result, design values have been adopted that are too conservative and make for inefficient use of lumber whose mechanical properties are ever decreasing.

There are several studies that have evaluated the effect of changing MC under a constant load for timber connectors (Keenan and others 1983, Kunesh and Johnson 1968, Mayo 1980, Noren 1968, Wilkinson 1971). The results of these studies share a common theme: The combined effect of changing environment with loading significantly decreased truss stiffness. In most cases, strength was also significantly reduced. However, the research neither quantified the effect of moisture cycling on stiffness or strength nor defined the level at which moisture cycling proved significant.

McAlister (1990) found that MPC joints containing laminated veneer lumber and pine and subjected to an outdoor environment for a l-year period showed a substantial decrease in stiffness and strength. The decrease in mechanical properties was due in part to “plate backout,” a phenomenon in which the metal plate backs out of the wood members due to shrinking and swelling stresses. Plate backout significantly weakens the interfacial contact between the metal-plate teeth and wood.

Recommended design values for truss members are dictated primarily by the materials comprising the truss, the type of truss, and the expected loading during the life of the truss (Truss Plate Institute 1985). The design plan laid out by architects and, to some degree, engineers, for a particular structure, generally dictates the type of trusses that will form the framework of the roof and floor systems. The required mechanical properties of the trusses are determined by the loadings as prescribed by local building codes. The truss manufacturer engineers the trusses based on design values that are concerned primarily with the lumber mechanical properties and the metal plate connectors (Truss Plate Institute 1985).

The lack of quantifying data regarding environmental and loading effects presents a difficulty in truss design. Design specifications for duration of loading based on the Madison Curve are available from the Truss Plate Institute located in Madison, WS. However, the effect of moisture cycling is compensated for

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by dividing the average load of (a) five moisture-controlled specimens (MC = 15 percent plus or minus 4 percent) by 3.0, or (b) five moisture-response specimens (MC = 15 percent assembly, then 7 percent, then greater than 10 percent) by 2.5. An adequate understanding of environmental variables on MPC joint behavior must be attained to knowledgeably assign design values for truss manufacture.

These environmental variables clearly need to be quantified for sensible design values to be assigned for MPC joints. Thus, the primary objective of this study was to quantify the effect of wood MC fluctuations on MPC joint behavior. Specifically, this study compared the effect of severity and number of wood moisture cycles with metal-plate **backout,** joint stiffness, critical slip, and strength. A secondary objective was to investigate maintaining inter-facial integrity between metal-plate teeth and wood by applying an epoxy adhesive at the interface and noting the changes in MPC joint mechanical behavior.

MATERIALS AND PROCEDURES

Experimental Design

A randomized block design, summarized in table 1, was used to minimize the high variability customarily seen in lumber mechanical properties. Two separate blocks were constructed to evaluate the effect of wood MC ranges and number of moisture cycles with various physical and mechanical properties of MPC joints. The two separate blocks were as follows: (1) standard MPC joints and (2) MPC joints with an adhesive applied at the tooth-wood interface.

Each block consisted of two factors: the severity of MC levels to which MPC joint specimens were subjected and the number of MC cycles. Ten replicates per cell were subjected to varying MC conditions (i.e., [al MC held constant at 12 percent, [b] MC cycled between 9 and 15 percent, and [cl MC cycled between 5 and 19 percent and a varying number of MC cycles from zero to eight-table 1). These replicates yielded a total of 150 MPC joint specimens per block (3 MC ranges times 5 MC cycles times 10 replicates = 150 specimens). Although the material used to construct the replicates in the blocks containing standard MPC joints and joints with an adhesive were from different boards, the boards were chosen so as to have comparable specific gravity and stiffness values between blocks, thus allowing for a relative comparison between blocks.

Lumber and Metal Plates

The MPC joints were constructed with No. 2 grade KD15 southern pine lumber representing a narrow range of specific gravities and moduli of elasticity. The lumber used to construct the MPC joints was nominal 2- by 4-inch dimension and 18-ft length and was sampled from a local lumber retailer located in central Louisiana. Modulus of elasticity (MOE) of each board was estimated by applying a static center-point load to each board oriented flatwise over a 16-ft span and measuring centerpoint deflection. Specific gravity was based on volume at the time of the test, and MC was determined on an approximately 1.5- by 1.5- by 3.5-inch block of wood removed adjacent to the metal plate after testing.

Table 1.—*Summary of experimental design showing the number of samples for each moisture cycle moisture range of no adhesive vs. adhesive metal-plate connector (MPC) joints for each number of moisture cycles*

Moisture content range	Number of moisture cycles				
	0	1	2	4	8
--- Percent ---	*Number of samples*				
No adhesive					
12	10	10	10	10	10
9 to 15	10	10	10	10	10
5 to 19	10	10	10	10	10
Adhesive					
12	10	10	10	10	10
9 to 15	10	10	10	10	10
5 to 19	10	10	10	10	10

The die-punched metal plates used in this study were standard truss-plate type plates made of 20-gauge grade C sheet metal, 3 inches wide by 4 inches long with an average tooth density of eight teeth per square inch. Average tooth length of the metal plates was 0.360 inch with teeth being pointed, slightly crimped, and having no surface coating or visible machining oil on the metal surface. The metal plates were not washed to remove any residual machining oil before joint assembly.

Joint Construction and Testing

Figure 1 shows a standard MPC joint used in this study. In accordance with Truss Plate Institute (1985), all teeth were removed within a lumber-end distance of 0.5 inch. The teeth were removed with a milling bit at the plate surface. Thirty-six pairs of teeth were present in the upper member, and 24 pairs were present in the lower member. This arrangement ensured failure in the lower member, which was equipped with linear variable differential transformers (LVDT).

An epoxy resin with a cure time of 15 minutes was applied with a sponge to the tips of the metal-plate teeth immediately before pressing into the wooden members preconditioned to an MC of 12 percent. An average of 0.0031 g of epoxy was applied to each tooth with the resin spread along the tooth length during pressing. Metal plates were pressed into the wooden members so as to make intimate contact, but not so much that the plate surfaces became embedded in the wood. The joints were placed in a hygrothermally controlled room at 79 °F and 66-percent relative humidity with an MC of approximately 12 percent after assembly for about 4 weeks to allow for relaxation of stresses induced by pressing. After conditioning, the joints were moisture cycled by placement in one of three hygrothermally controlled units set to cycle between the following MC ranges: 5 to 19 percent, 9 to 15 percent, and 12 percent (constant). All moisture was atmospheric in nature, and at no time were the joints exposed to direct surface water. Moisture content was monitored during cycling with a hand-held surface moisture meter. All joints were reconditioned to an MC of 12 percent for 4 weeks prior to testing.

Loading was applied in tension by a 30,000-lb capacity, screw-driven crosshead testing machine (fig. 1). A constant displacement rate of 0.015 inch/min was applied so as to produce failure in 5 to 10 minutes.

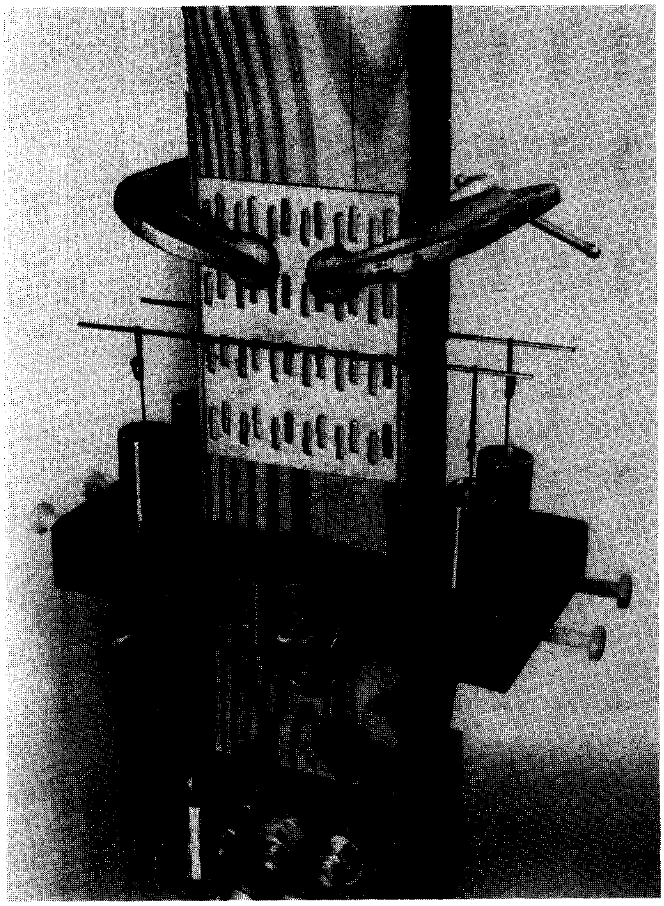

Figure 1.— *Typical metal-plate connectorjoint specimen before tensile testing.*

The specimen was attached to the testing machine with universal joints to prevent potential moments induced by misalignment. The upper member slip was restrained by the attachment of two C-clamps. Four simultaneous LVDT readings were taken every second, located in pairs at the two opposite sides of the wood-wood juncture (fig. 1). These LVDT values were then averaged to provide overall slip between the metal plate and lower wood member. Load was monitored with a 10,000-lb capacity load cell. A computer-controlled data acquisition system acquired the load and slip readings. Load-slip traces were standardized to an MC of 12 percent by adjusting mechanical properties by 5 percent per l-percent MC change (Bodig and Jayne 1982).

Metal-plate backout is defined in this study as the dimensional difference between the wooden member thickness and the wood-plus-plate thickness. This method was chosen so as to minimize errors due to wood dimensional changes related to stress relaxation or MC. The wood-plus-plate thickness was measured preceding and after MC conditioning; the dimension was based on the average of two readings located on each side of the long axis center line of the metal plate and midway between the rows of teeth. Wood-member dimensions were recorded at the same time. Initial stiffness was calculated as the slope of the load-slip curve between 700 and 1,100 lb.

RESULTS AND DISCUSSION

The conditioning history of the moisture-cycled specimens is shown in figure 2. The moisture history for the constant 12-percent MC specimens is not shown due to the lack of moisture fluctuations. The compressor motor needed maintenance during the sixth and seventh cycles in the mild-cycle conditioning chamber, whereas compressor problems were encountered during the fifth cycle in the more severe cycle conditioning chamber. The duration of each moisture cycle varied with the operation of the conditioning chambers and was coordinated to be of about equal length for both conditioning chambers.

Some of the physical properties of the MPC joints at the time of the test are shown in table 2. The MC and specific gravity of standard MPC joints and those joints with an adhesive interface were very similar. The average moduli of elasticity from static, flatwise bending tests of the lumber comprising standard and adhesive MPC joints were 1.76 (10^6) psi and 1.86 (10^6) psi.

Plate Backout

Plate backout was significantly affected by the severity and number of moisture cycles as seen in figure 3.

Table 2.-*Average value by moisture content mnge and number of cycles for selected physical and mechanical properties of metal-plate connector (MPC) joints tested in this study*

Moisture content range	No. of Cycles	Moisture content		Specific gravity		Plate backout		Plate backout		Ultimate load		Stiffness		Load-at-0.015-inch-slip	
		No adh.	Adhesive	No adh.	Adhesive	No adh.	Adhesive	No adh.	Adhesive	No adh.	Adhesive	No adh.	Adhesive	No adh.	Adhesive
Percent		*Percent*				*Inches*		*Percent tooth length*		*Lb*		*Kips/inch**		*Lb*	
12 (constant)	0	12.1	12.1	0.49	0.49	0.002	0.000	0.6	0.1	4,080 (11.2)†	4,431 (6.4)	729 (14.6)	1,422 (18.5)	3,612 (9.9)	4,285 (7.4)
	1	11.4	11.6	0.48	0.48	0.002	0.005	0.6	0.1	3,907 (8.3)	4,367 (7.4)	677 (12.8)	1,316 (13.2)	3,513 (7.6)	4,261 (8.8)
	2	11.3	11.3	0.49	0.49	0.004	0.004	1.1	1.1	3,778 (7.0)	4,201 (6.1)	613 (9.5)	1,017 (15.2)	3,462 (7.2)	4,062 (7.6)
	4	10.3	10.4	0.47	0.49	0.004	0.007	1.2	1.8	3,598 (5.9)	4,095 (7.3)	565 (17.2)	853 (20.9)	3,304 (6.8)	3,856 (9.6)
	8	11.2	11.1	0.49	0.47	0.004	0.003	1.2	0.8	3,490 (9.4)	3,979 (8.9)	522 (14.2)	687 (15.2)	3,185 (10.4)	3,758 (9.2)
9 to 15	0	12.1	12.1	0.49	0.49	0.002	0.000	0.6	0.1	4,080 (11.2)	4,431 (6.4)	729 (14.6)	1,422 (18.5)	3,612 (9.9)	4,286 (7.4)
	1	12.0	12.0	0.49	0.48	0.006	0.008	1.7	2.2	3,821 (8.4)	4,035 (6.6)	472 (14.4)	619 (8.4)	3,389 (8.3)	3,850 (7.3)
	2	10.8	10.8	0.49	0.48	0.007	0.010	2.1	2.8	3,585 (8.0)	3,899 (5.6)	383 (10.7)	532 (8.0)	3,187 (7.4)	3,652 (7.8)
	4	10.1	10.2	0.49	0.49	0.013	0.014	3.5	4.0	3,421 (8.7)	3,694 (6.7)	364 (15.3)	470 (16.1)	3,020 (9.7)	3,428 (7.7)
	8	11.3	11.3	0.49	0.49	0.012	0.015	3.3	4.2	3,312 (8.6)	3,596 (8.1)	335 (14.1)	471 (16.6)	2,878 (7.7)	3,375 (8.2)
5 to 19	0	12.1	12.1	0.49	0.49	0.002	0.000	0.6	0.1	4,080 (11.2)	4,431 (6.4)	729 (14.6)	1,422 (18.5)	3,612 (9.9)	4,285 (7.4)
	1	11.6	12.1	0.48	0.47	0.013	0.011	3.6	3.0	3,545 (11.8)	3,752 (6.1)	366 (13.7)	466 (12.5)	3,127 (10.1)	3,503 (6.5)
	2	10.3	10.3	0.49	0.49	0.023	0.016	6.4	4.4	3,199 (12.6)	3,438 (9.9)	271 (14.1)	358 (11.1)	2,725 (10.5)	3,174 (9.4)
	4	10.5	11.0	0.48	0.49	0.037	0.027	10.1	7.6	3,027 (18.8)	3,241 (9.4)	267 (20.2)	336 (13.7)	2,575 (14.3)	2,954 (10.1)
	8	11.4	11.4	0.51	0.48	0.061	0.045	17.0	12.5	2,812 (17.2)	2,980 (12.8)	249 (20.0)	295 (14.2)	2,457 (15.9)	2,678 (11.6)

*Kips = kilopounds

+&efficient of variation in parenthesis

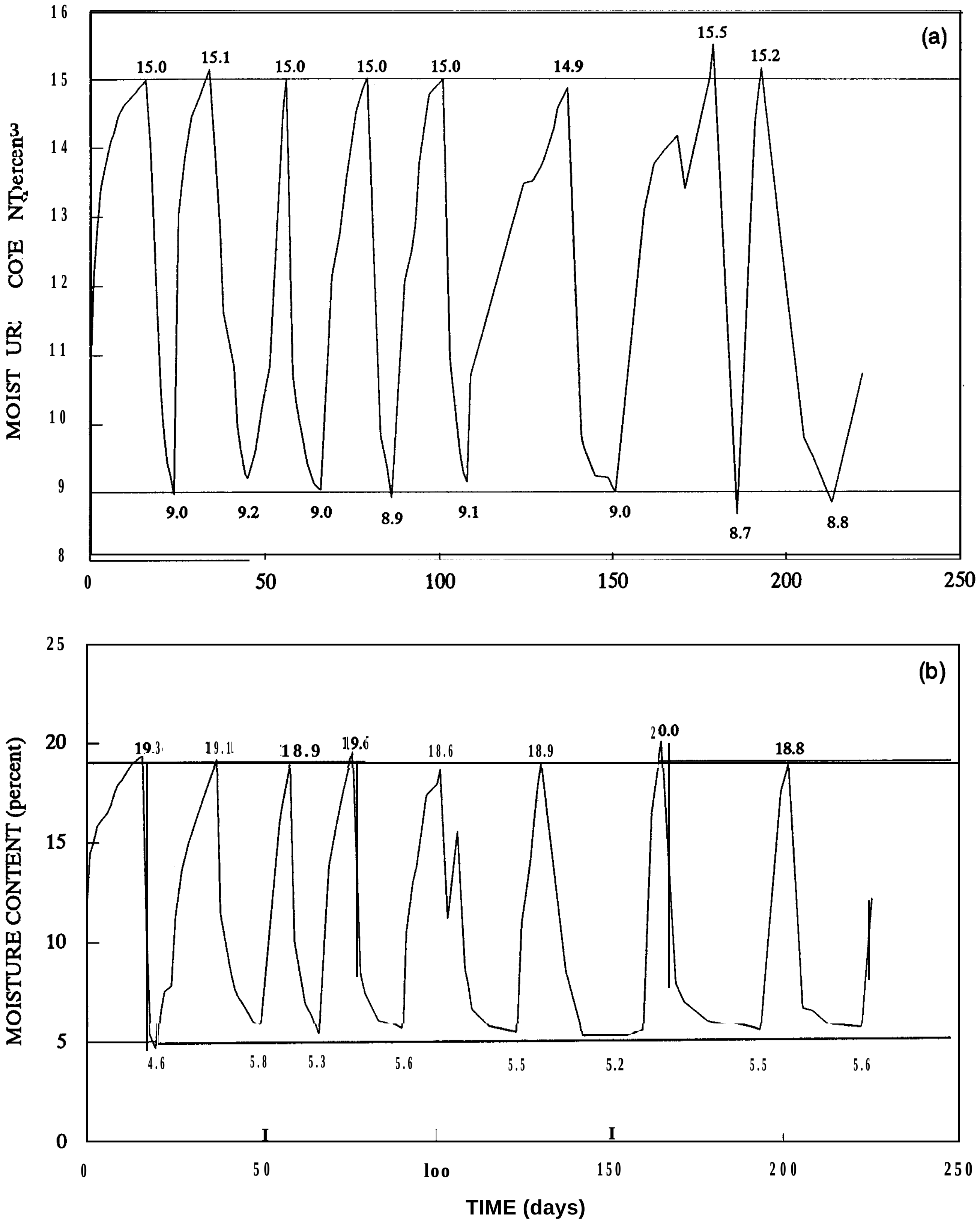

Figure *2.-Moisture history of metal-plate connector joints that were cycled between (a) 9- and* ***15-percent*** *moisture content (MC) and (b) 5- and* ***19-percent*** *MC.*

Numerical values of plate **backout** are also shown in table 2. The MPC joints held at a constant la-percent MC showed plate **backout** values of approximately 1 percent of the total tooth length. The mild moisture-cycled specimens seemed to stabilize at about 4 percent of total tooth length after eight moisture cycles. In both the constant la-percent MC and mild moisture-cycled specimens, addition of an adhesive had no apparent effect on plate **backout.**

The more severe moisture-cycled standard and adhesive MPC joints backed out 17 percent and 12.5 percent of the total tooth length after eight moisture cycles. Unlike the constant la-percent MC and mild moisture-cycled specimens, the rate of plate **backout** for the more severe moisture-cycled specimens showed no signs of leveling off. Addition of an adhesive to the tooth-wood interface retarded plate **backout,** but the adhesive specimens did continue to back out after eight moisture cycles. This suggests that plate **backout** continues for an extended period of time for MPC joints subjected to wide variations in MC. A similar study, but of an extended timeframe, may help to define the upper limit of this variable.

Mechanical Behavior

Load-slip traces for standard MPC joints subjected to a constant la-percent MC, mild moisture cycles, and more severe moisture cycles are shown in figure 4, with the adhesive tooth-wood interface counterparts summarized in figure 5. Average load-slip traces (measured in kips, or kilopounds) along with plus and minus one standard deviation for adhesive and standard joints after zero, one, two, four, and eight moisture cycles are shown in the appendix.

Figure 4 shows that successive moisture cycles do appear to change the nature of the load-slip traces. Metal-plate connector joints subjected to a constant MC exhibited a slight degradative behavior with time. This is to be expected to localize relaxation of the wood surrounding the tooth. Although the MPC joints exhibited diminished load-slip traces with time, each trace exhibited nonlinear behavior throughout the entirety of the loading.

Moisture cycling not only accelerated the **rheological** degradation of the MPC joints but also changed the shape of the load-slip trace (fig. **4b, 4c).** Mild moisture cycling of the MPC joints reduced the amount of nonlinearity in the initial portions of the load-slip traces, a factor more evident with each subsequent moisture cycle. This effect is even more apparent in the more severe moisture-cycled MPC joints, with the load-slip traces remaining almost linear up until approximately 50 percent of the ultimate load. This suggests that a different stress transfer mechanism is being demonstrated. This altered mechanism is most likely a result, either singularly or in concert, of less surface area between the tooth and wood due to plate **backout,** accelerated localized relaxation of the wood surrounding the teeth, and/or an additional rotational load being applied to the teeth due to eccentric loading of the backed-out plate (**Chou** 1987, Groom 1988).

This same phenomenon was also present in the MPC joints with an adhesive tooth-wood interface (fig. 5). The adhesive interface appeared to remain intact for constant MC specimens. However, moisture cycling degraded the adhesive interface rather rapidly, with most of the degrade occurring in the first moisture cycle.

The addition of an adhesive to the tooth-wood interface reduced the variation in load-slip traces of MPC joints (appendix). Table 2 and figures Al, A3, A5, A7, and A9 show that the variability of standard MPC joints increased with the severity and number of moisture cycles. The tooth-wood interface of adhesive MPC joints maintained more intimate contact during moisture cycling, resulting in mechanical performance variability that seems little affected by moisture cycling (table 2; figs. A2, A4, A6, **A8,** and **A10).** This suggests that the most important attribute of the adhesive interface may not be the average increase in mechanical performance that degraded during subsequent moisture cycling, but instead the reduced variability associated with moisture cycling.

Ultimate Load.-The effect of moisture cycling on ultimate load is summarized in figure 6 and table 2. The MPC joints with an adhesive interface had ultimate-load values about 9 percent higher than the standard joints. This difference may be partially due to the different lumber samples used for the adhesive and standard joints. Although the specific-gravity values of the two samples were identical, the MOE of the adhesive joints was about 6 percent higher than that of the standard joints.

The decrease in ultimate load for subsequent moisture cycles was consistent in both adhesive and standard MPC joints (table 3). The percentage decrease in ultimate load after eight moisture cycles for constant la-percent MC, mild moisture-cycled, and more severe moisture-cycled specimens was approximately **10, 20,** and 30 percent, respectively. The rate of decrease also seemed to decline for all specimens with subsequent moisture cycles. However, the number of moisture cycles in this study was inadequate for determining a lower limit for each moisture range.

Figure 7 shows that an inverse relationship existed between plate **backout** and ultimate load. Kline (1993) reported a similar relationship for MPC joints not subjected to moisture cycling. This study showed that the ultimate load of standard MPC joint specimens held at a constant la-percent MC decreased at a much faster rate than did the severely cycled specimens for a given degree of plate **backout,** with the mild **mois-**

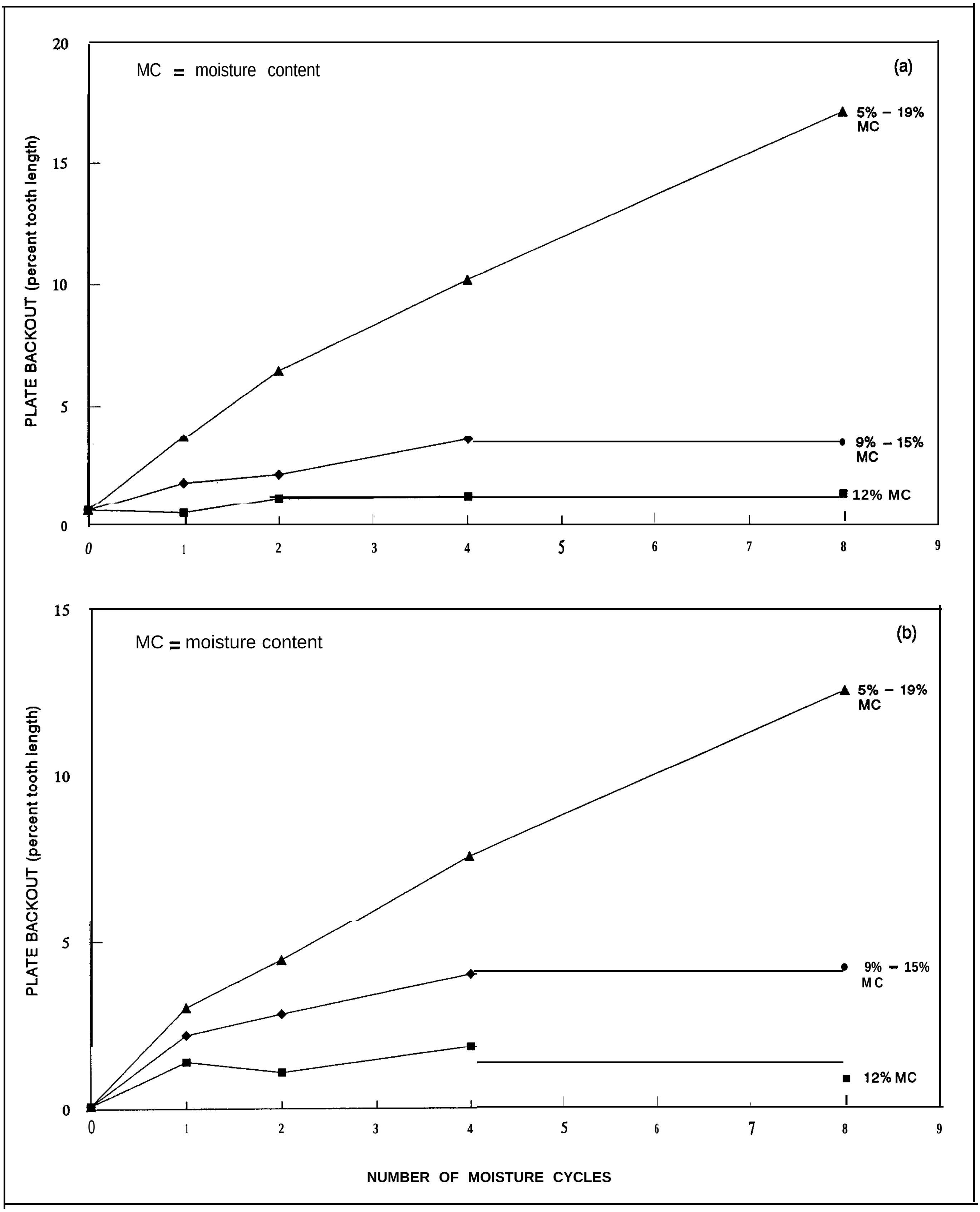

Figure 3.-Effect *of number and severity of moisture cycles on plate backout of metal-plate connector joints (10 replicates per* data *point) constructed (a) without an adhesive interface and (b) with an epoxy adhesive interface.*

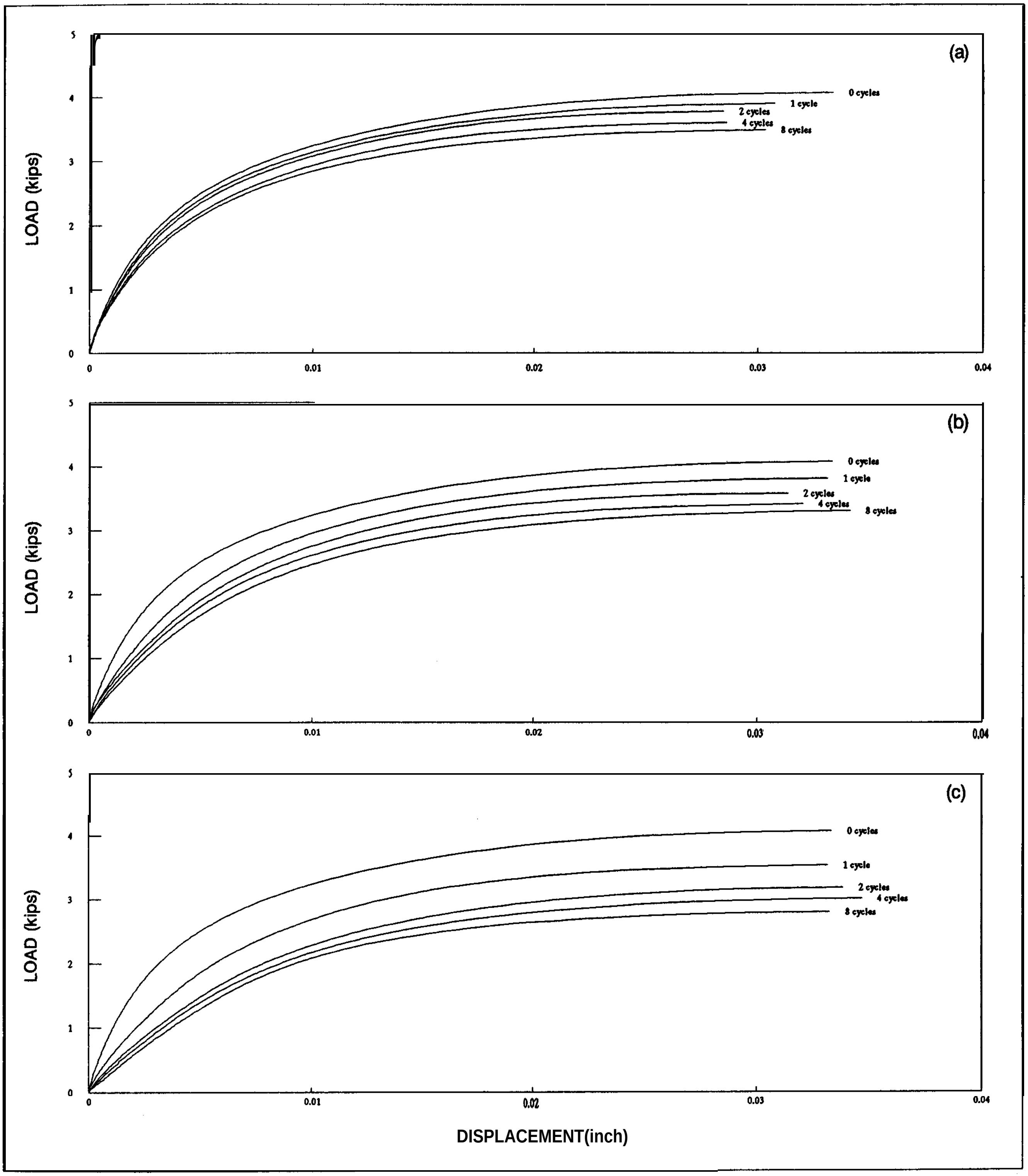

Figure 4.-*Load-slip traces in kips (kilopounds) showing the effect of sequential moisture cycling for standard metal-plate connector joint specimens (10 replicates per moisture-content cycle) subjected to (a) constant 12-percent moisture content (MC), (b) moisture cycling between 9- and lb-percent MC, and (c) moisture cycling between 5- and 19-percent MC.*

Table 3.— *Percentage decrease, based on zero moisture cycles, by moisture content range and number of cycles of selected mechanical properties*

Moisture content range	No. of cycles	Ultimate load		Stiffness (*Kips* / inch*)		Load-at-0.015-inch-slip	
		No adh.	Adhesive	No adh.	Adhesive	No adh.	Adhesive
		Percent					
12 (constant)	0	0.0	0.0	0.0	0.0	0.0	0.0
	1	4.2	1.5	7.2	7.5	2.7	0.6
	2	7.4	5.2	15.9	28.5	4.2	5.2
	4	11.8	7.6	22.5	40.0	8.5	10.0
	8	14.5	10.2	28.4	51.7	11.8	12.0
9 to 15	0	0.0	0.0	0.0	0.0	0.0	0.0
	1	6.4	8.9	35.2	56.4	6.2	10.1
	2	12.1	12.0	47.4	62.6	11.8	14.8
	4	16.2	16.6	50.1	66.9	16.4	20.0
	8	18.8	18.8	54.0	66.9	20.3	21.2
5 to 19	0	0.0	0.0	0.0	0.0	0.0	0.0
	1	13.1	16.3	49.8	67.2	13.4	18.3
	2	21.6	22.4	62.8	74.8	24.6	25.9
	4	25.8	26.8	63.4	76.4	28.7	31.1
	8	31.1	32.8	65.9	79.3	32.0	37.5

*Kips=kilopounds.

ture-cycled specimens falling between the two moisture ranges (fig. 7a). Because MPC joints in service are subjected to varying moisture cycles as well as in-service loads, it is difficult to develop a simple predictive equation for plate backout and ultimate load due to other compounding factors.

Initial *Stiffness*.—The initial stiffness of MPC joints is the mechanical property most affected by moisture hysteresis, with results shown in figure 8 and tables 2 and 3. Metal-plate connector joints kept at a constant la-percent MC showed a steady reduction in initial stiffness for the first several months, with a reduced rate of degradation in the following months. These constant la-percent MC specimens showed about a 30-percent reduction in initial stiffness over the approximate g-month timeframe, with a lower limit appearing to be about 35 percent of the original initial stiffness.

Moisture cycling significantly increased the degradation of MPC joint initial stiffness, especially with regard to the first moisture cycle (fig. 8a). Mild moisture-cycled specimens showed a drop in initial stiffness of 35 percent after the first moisture cycle. Subsequent moisture cycling resulted in a 54-percent reduction in initial stiffness, with a lower limit appearing to be about 60 percent of the original initial stiffness. More severe moisture cycling resulted in a 50-percent reduction in initial stiffness after only one moisture cycle. Subsequent moisture cycles had a minimal effect, with a lower limit of approximately 70 percent of the original initial stiffness.

Metal-plate connector joints with an adhesive interface showed a heightened response of initial stiffness to moisture cycling (fig. 8b). In the constant la-percent MC specimens and the mild and more severe moisture-cycled specimens, the initial stiffness of the adhesive interface MPC joints approached that of the standard MPC joints with each successive moisture cycle. The difference between the adhesive interface and standard MPC joints diminished with the severity of the moisture cycling. Although the initial stiffness of the adhesive interface MPC joints diminished more rapidly than that of standard MPC joints, the adhesive interface joints were still stiffer than standard joints in all cases.

Load-at-0.016-Inch-SZip.-Load-at-O.OlB-i,nch-slip was recorded instead of the traditional load-at-0.030-inch-slip as the top member of the joint was restrained and only the load-slip trace of the bottom member was recorded (fig. 1). Load-at-0.015~inch-slip followed a trend similar to the ultimate load of the MPC joints, with strength reductions of about 10 percent, 20 percent, and 30 percent for constant la-percent MC specimens, mild-cycled specimens, and more severe cycled specimens, respectively (fig. 9). Adhesive interface specimens also showed an increase in load-at-0.015-inch-slip for all moisture-cycled specimens, along with a similar pattern of load-at-O.Olb inch-slip degradation. Metal-plate connector joints with an adhesive interface did show an accelerated degrade in load-at-0.015~inch-slip, with successive moisture cycles when compared to standard MPC joints, especially with regard to the first moisture cycle. This is most likely due to weakening of the adhesive interface caused by dimensional changes in the wood surrounding the teeth of the metal plate.

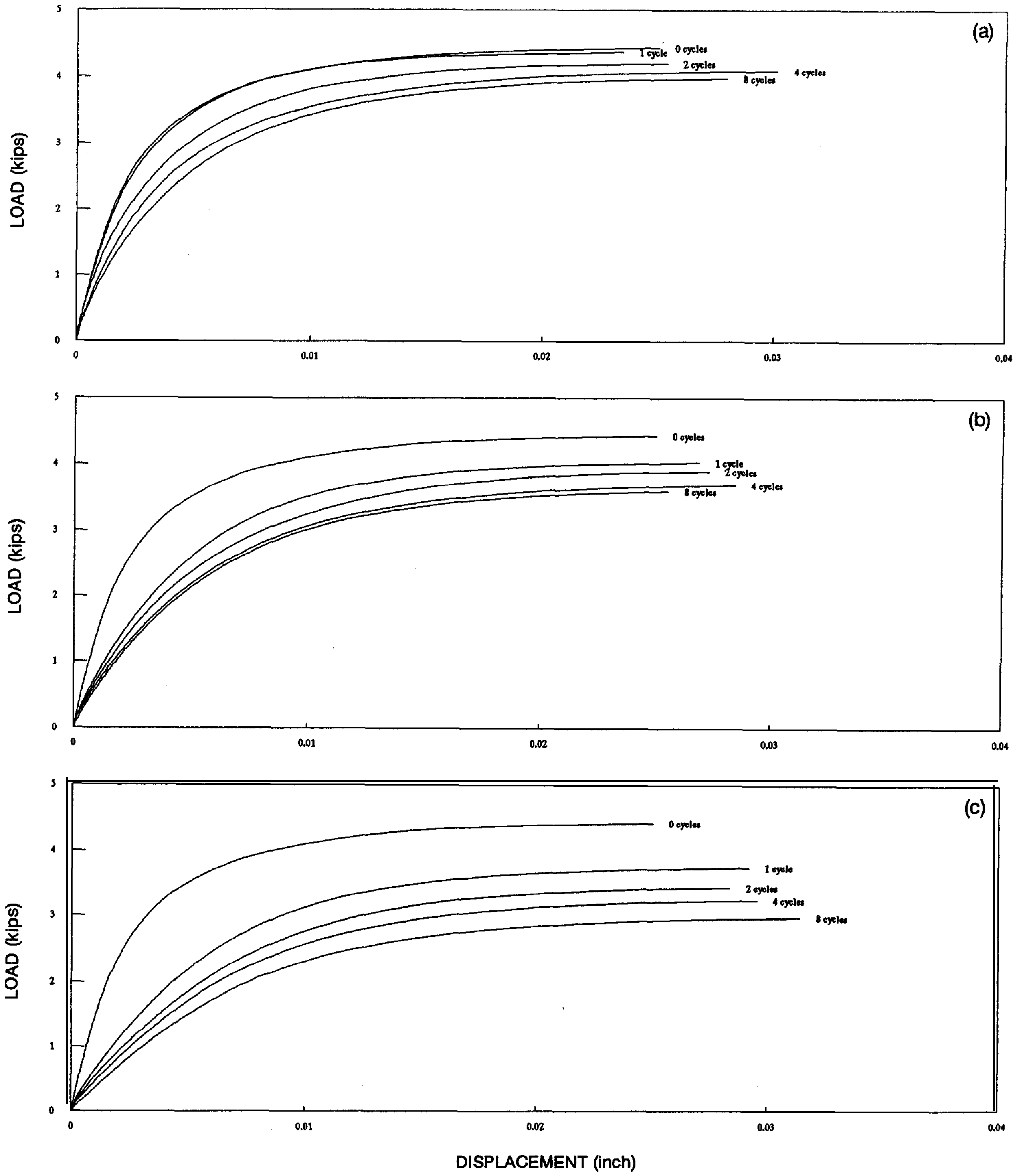

Figure 5.—*Load-slip traces in kips (kilopounds) showing the effect of sequential moisture cycling for adhesive interface metal-plate connector joint specimens (10 replicates per moisture-content cycle) subjected to (a) constant 12-percent moisture content (MC), (b) moisture cycling between 9- and 15-percent MC, and (c) moisture cycling between 5- and 19-percent MC.*

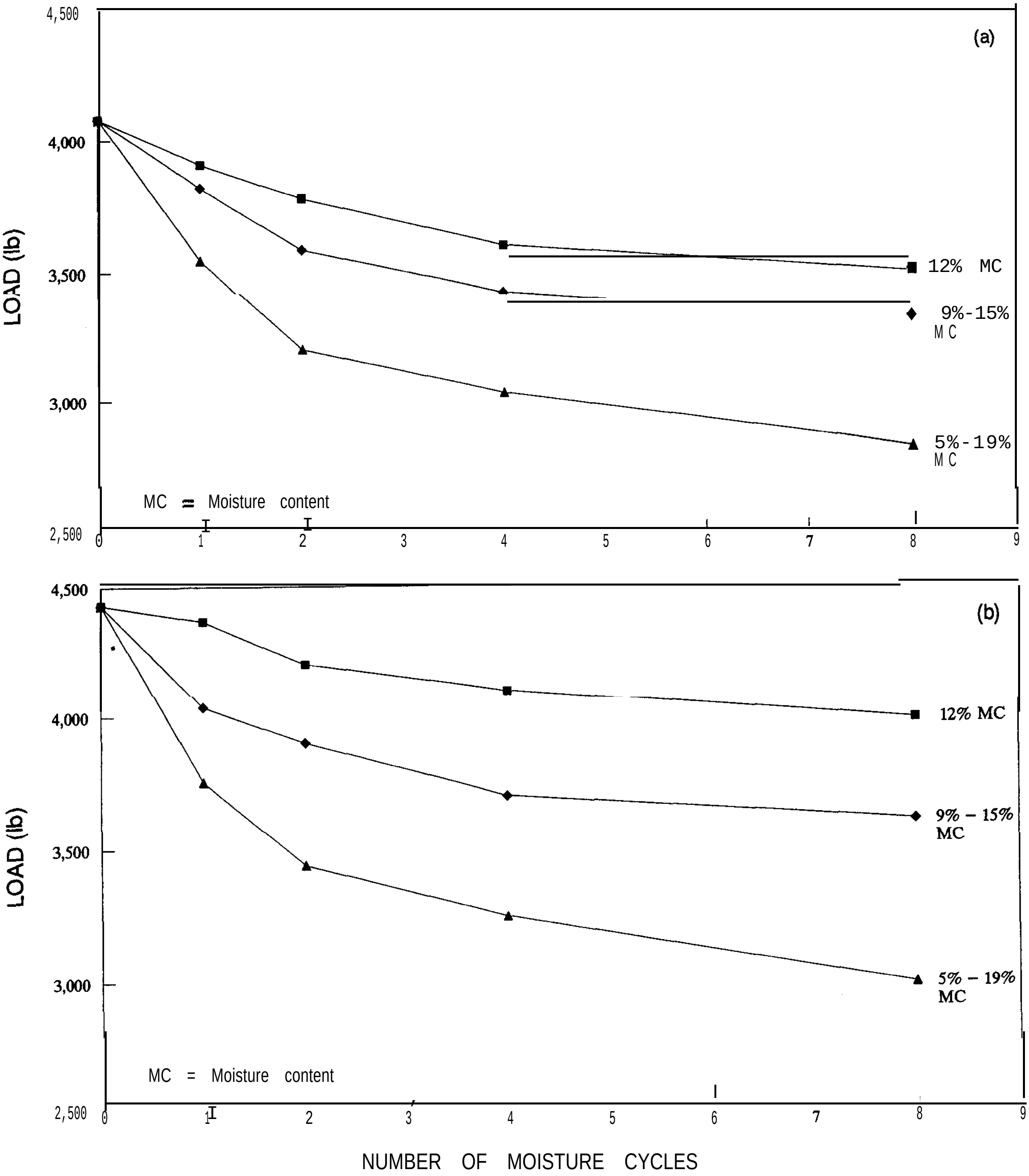

Figure 6.-Effect *of number and severity of* **moisture** *cycles on ultimate load of metal-plate connector joints (10 replicates per data point) constructed (a) without an adhesive interface and (b) with an epoxy adhesive interface.*

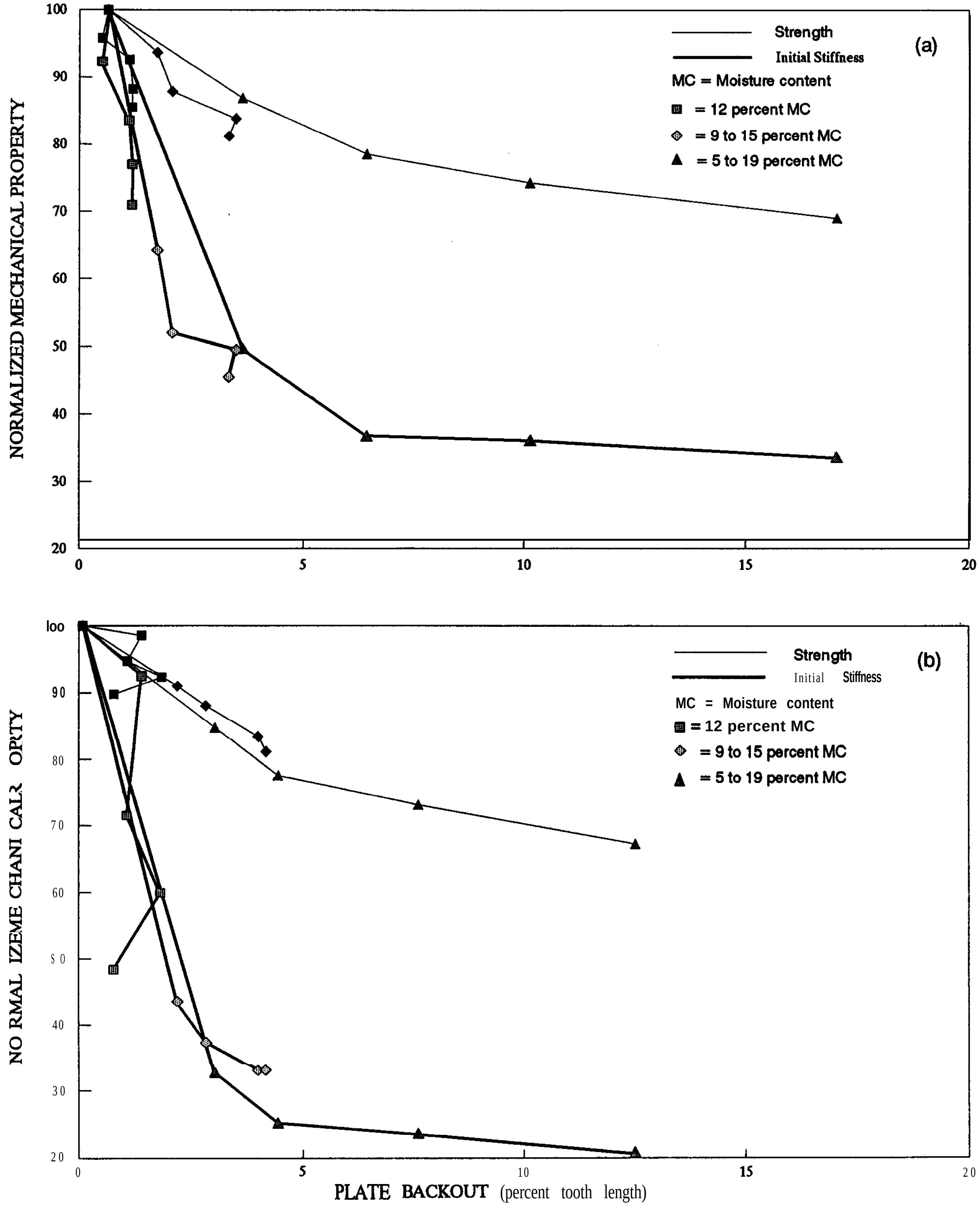

Figure 7.-Effect of plate backout on the normalized ultimate load and normalized initial stiffness of metal-plate connector joints (10 replicates per data point) constructed (a) without an adhesive interface and (b) with an epoxy adhesive interface.

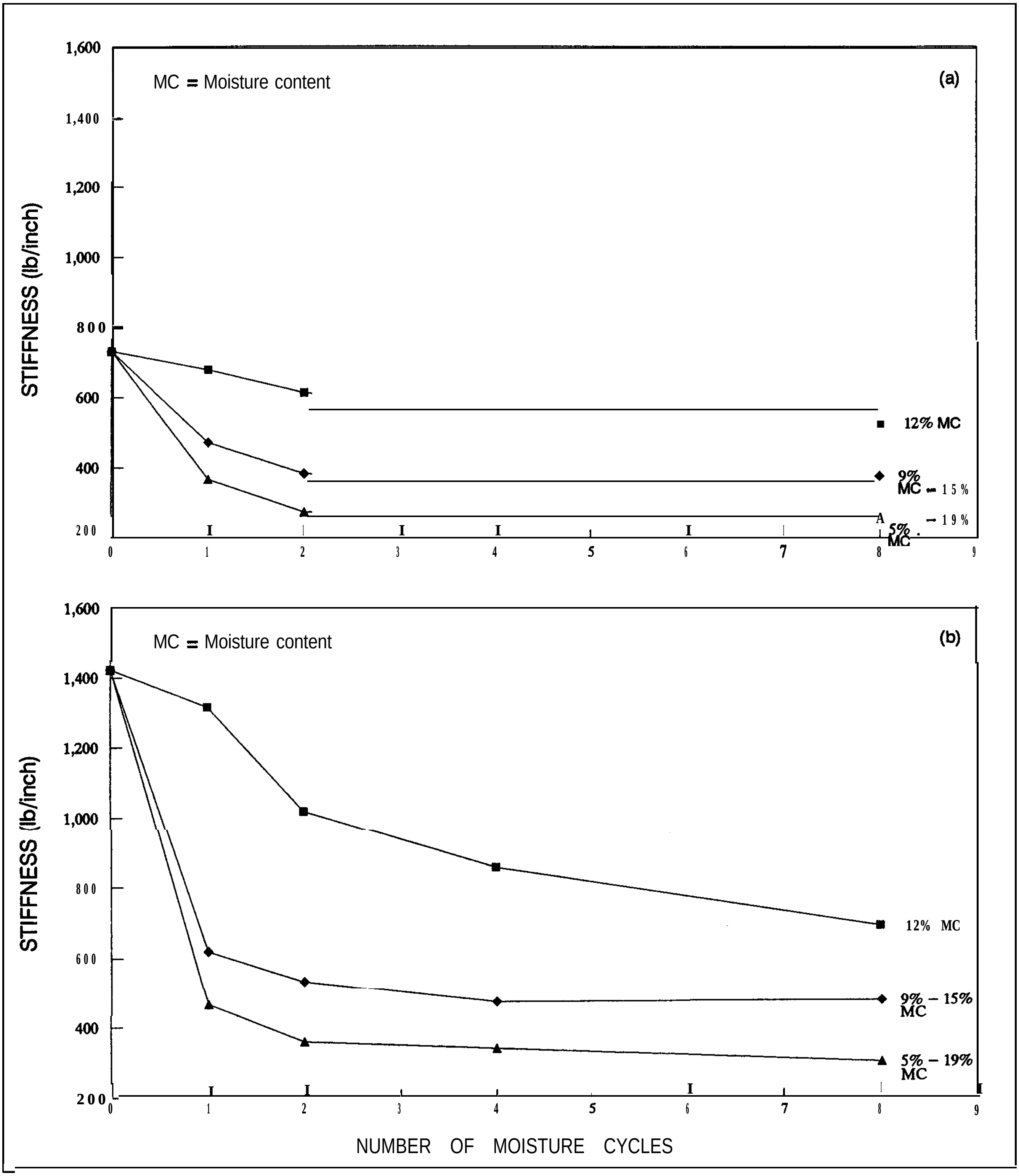

Figure 8.— Effect of number and severity of moisture cycles on initial stiffness of metal-plate connector joints (10 replicates per data point) constructed (a) without an adhesive interface and (b) with an epoxy adhesive interface.

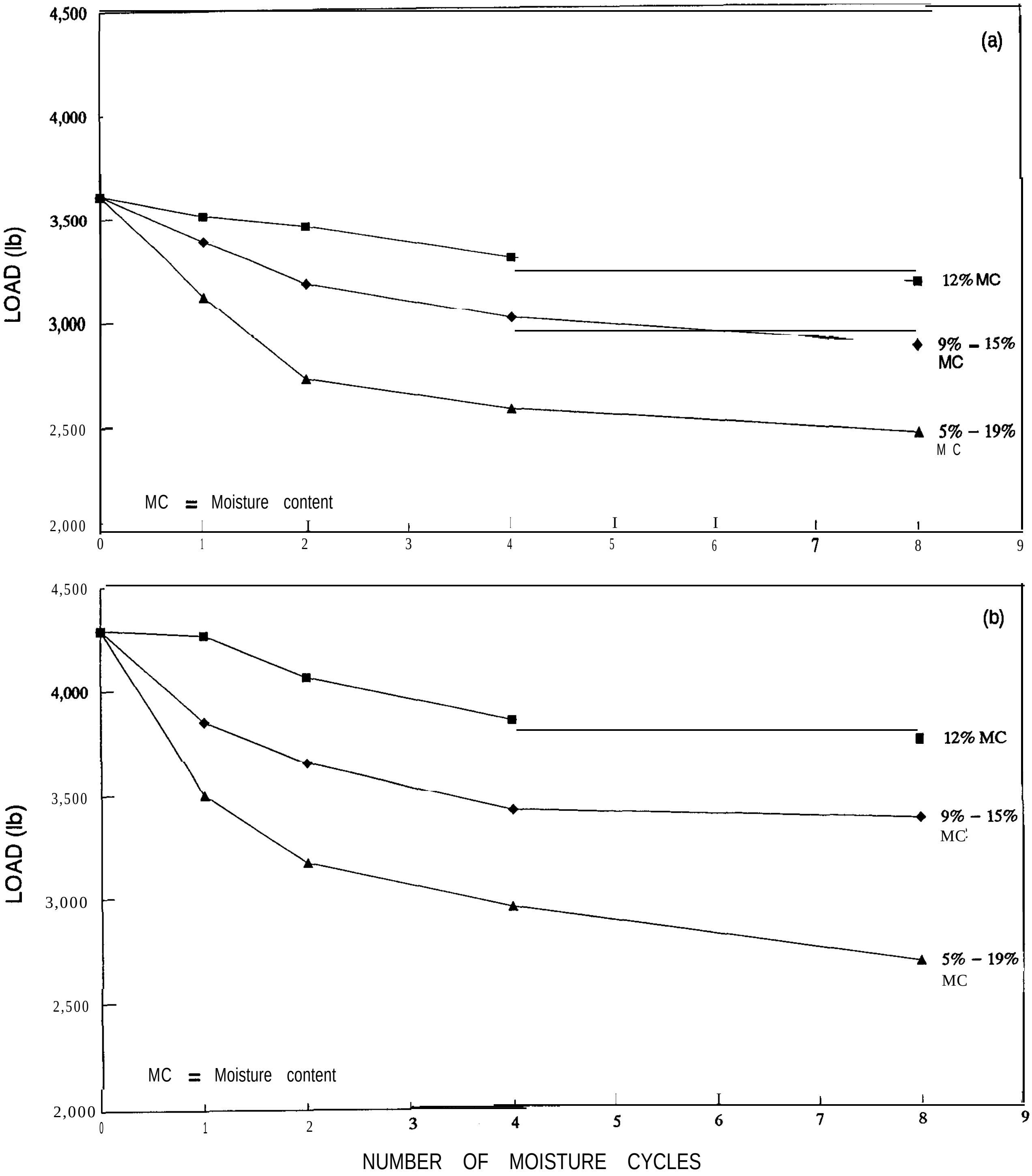

Figure 9.-Effect of number and severity of moisture cycles on load-at-0.015~inch-slip of metal-plate connector joints (10 replicatesper data point) constructed (a) without an adhesive interface and (b) with an epoxy adhesive interface.

CONCLUSIONS

Moisture cycling significantly affects the mechanical behavior of MPC joints. Some of the decline in mechanical behavior could be attributable to plate backout, which was as high as 17 percent of the total tooth length for more severe moisture-cycled specimens. Specimens subjected to a constant la-percent MC over the timeframe exhibited curvilinear load-slip traces. However, more severe moisture cycling resulted in an almost linear load-slip trace up to about 50 percent of the ultimate load, followed by a curvilinear response to failure. Thus, it appears that there is a change in the stress transfer mechanism for moisture-cycled specimens. Although the average load-slip traces of standard MPC joints are degraded by both severity and number of moisture cycles, the real gain in design values by addition of an adhesive interface between the tooth and wood may be in variability of these traces, which is much less affected by moisture cycling.

Initial stiffness of the load-slip traces was most drastically affected by moisture cycling, with reductions of approximately 30 percent, 55 percent, and 65 percent for constant la-percent MC, mild moisture-cycled, and more severe moisture-cycled specimens, respectively. Ultimate load was less severely affected, with constant la-percent MC, mild moisture-cycled, and more severe moisture-cycled specimens reduced approximately 15 percent, 20 percent, and 30 percent, respectively. However, a study of longer duration is necessary to determine the lower limit for each moisture range. Load-at-0.015-inch-slip showed reductions similar to ultimate load.

It appears that addition of an adhesive interface between the teeth and wood increases the mechanical properties of MPC joints. However, the apparent increase in mechanical properties could not be quantified due to the lack of identically matched specimens. The degrade of ultimate load and load-at-0.015-inch-slip of adhesive interface MPC joints was similar to that of standard MPC joints. Initial stiffness of adhesive interface MPC joints degraded more rapidly than standard MPC joints, probably due to weakening of the adhesion between the teeth and wood. Increased adhesion between the metal plates and wood, either through plate cleaning or improved adhesive system, would most likely further enhance structural performance.

It should be noted that in-service MPC joints most commonly are subjected to MC somewhere between the la-percent constant and mildly cycled specimens. Caution should be exercised when applying the results of this study to different metal-plate types and to in-service structures because of factors that have been ignored in this study, such as surface moisture and in-service loading of the truss structures.

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APPENDIX

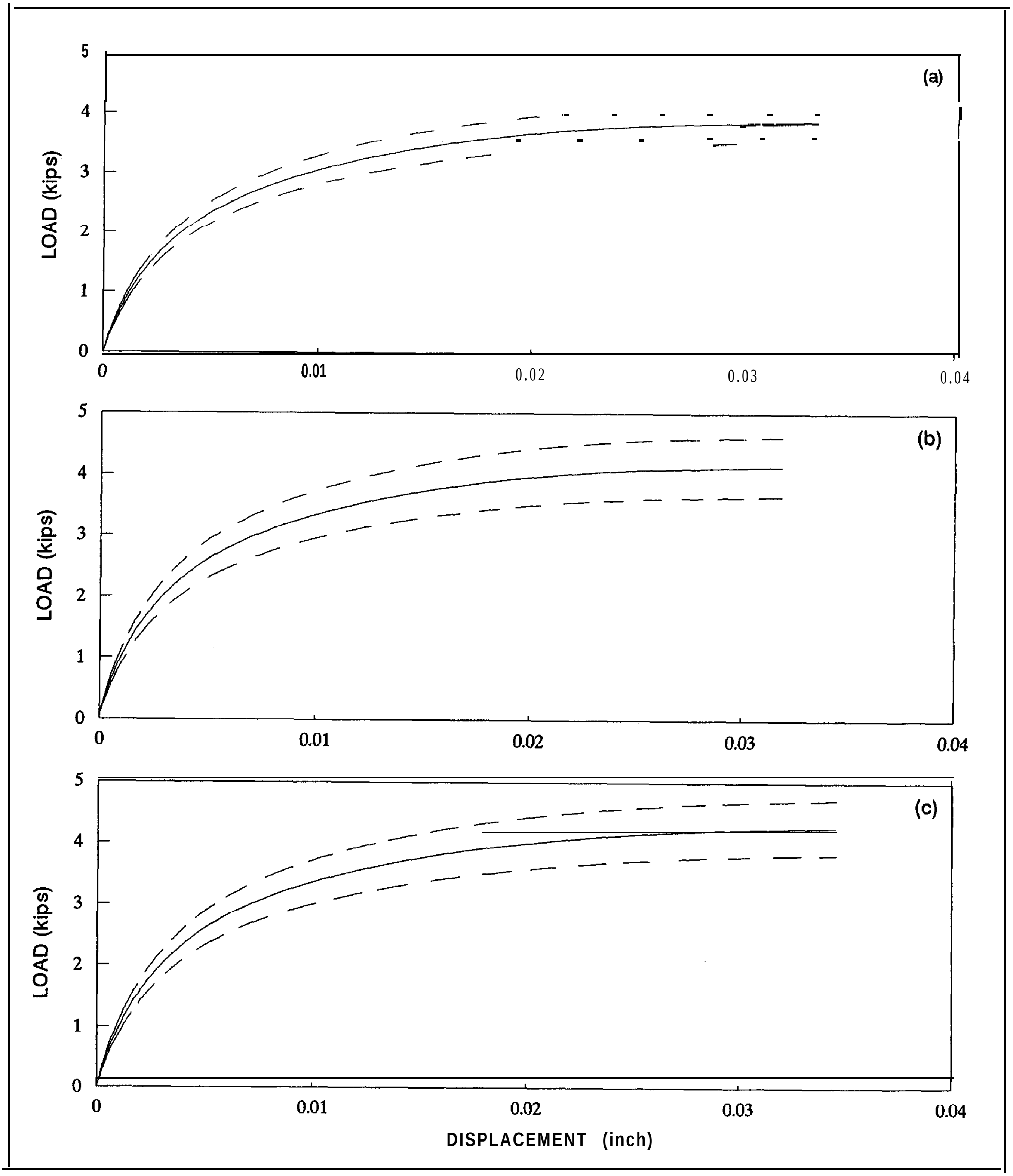

Figure A1.—*Average load-slip traces (solid lines), includingplus and minus one standard deviation (broken lines), for standard metal-plate connector joints subjected to zero moisture cycles and (a) constant 12-percent moisture content (MC), (b) moisture cycling between 9- and 15-percent MC, and Cc) moisture cycling between 5- and 19-percent MC.*

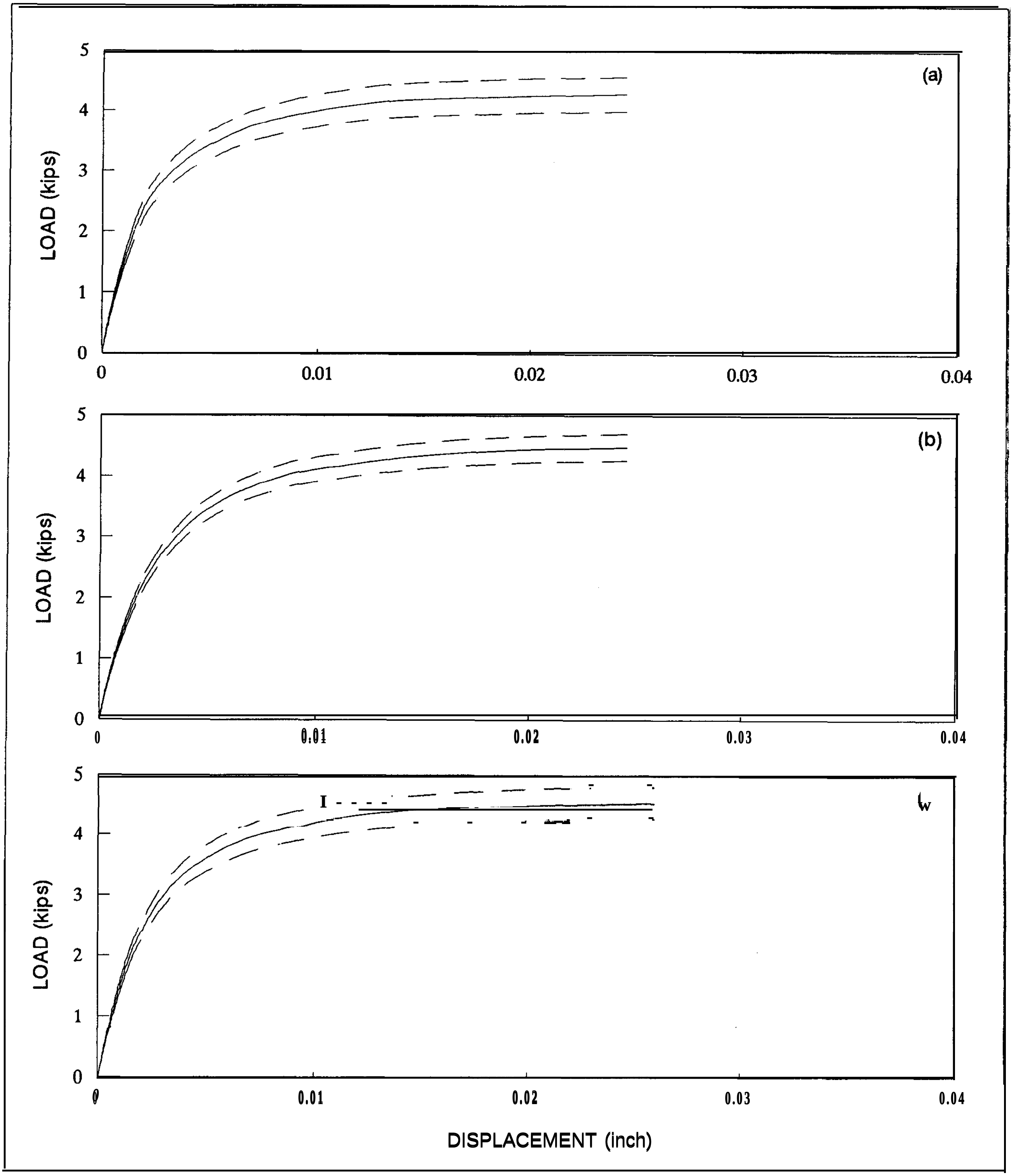

Figure A2.— Average load-slip traces (solid lines), including plus and minus one standard deviation (broken lines), for adhesive interface metal-plate connector joints subjected to zero moisture cycles and (a) constant 12-percent moisture content (MC), (b) moisture cycling between 9- and 15-percent MC, and (c) moisture cycling between 5- and 19-percent MC.

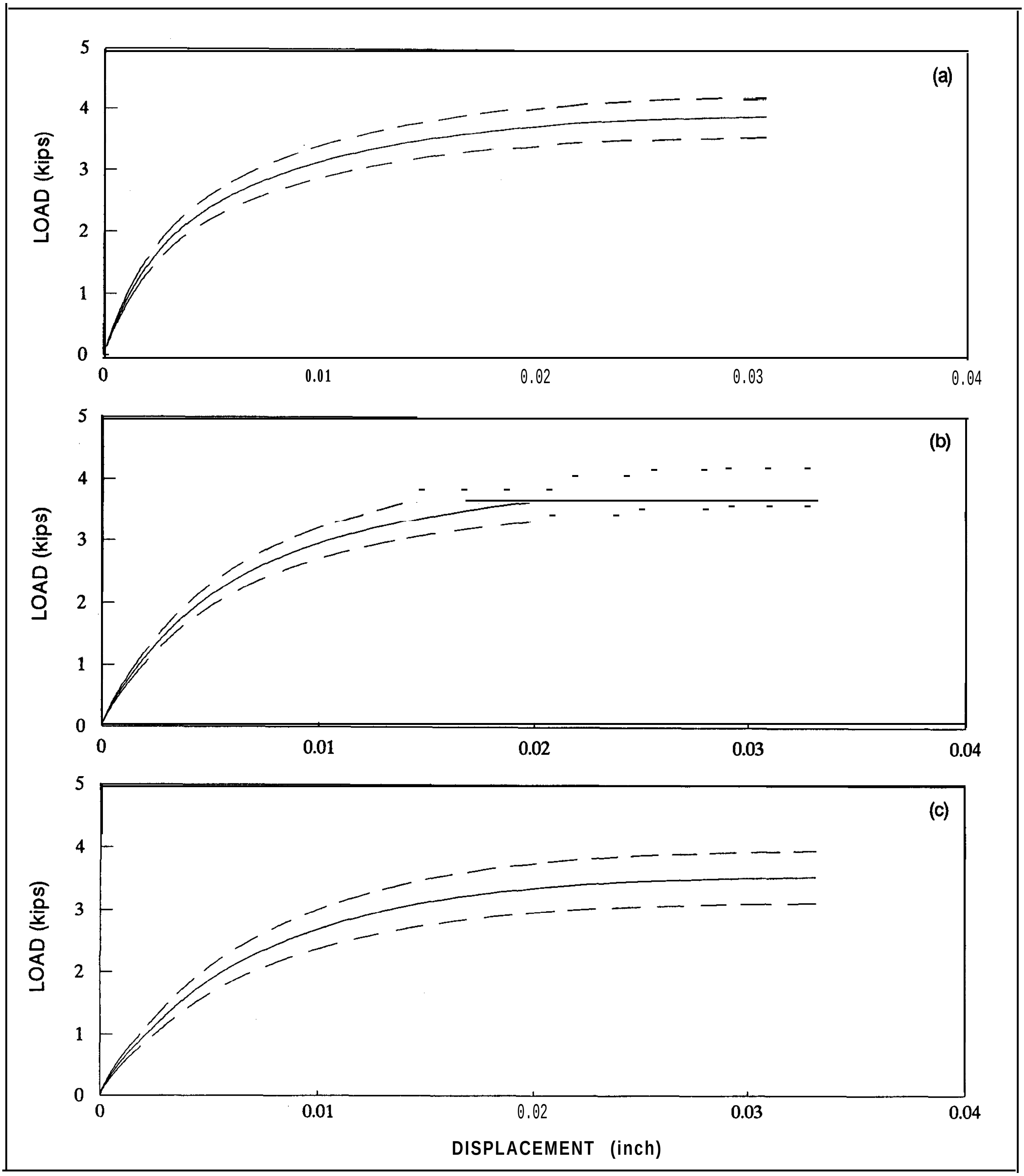

Figure A3.— *Average load-slip traces (solid lines), including plus and minus one standard deviation (broken lines), for standard metal-plate connector joints subjected to one moisture cycle and (a) constant 12-percent moisture content (MC), (b) moisture cycling between 9- and 15-percent MC, and (c) moisture cycling between 5- and 19-percent MC.*

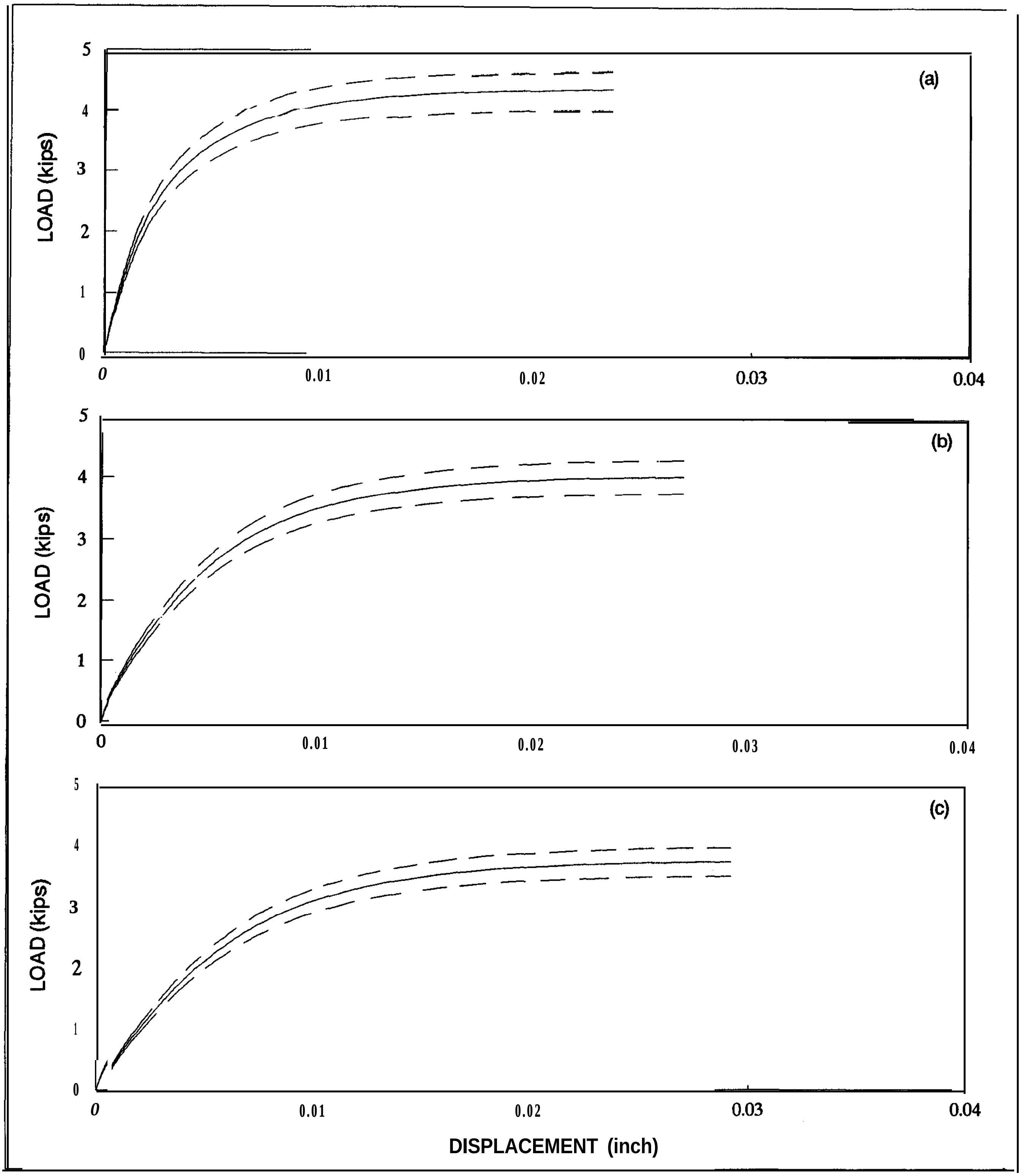

Figure A4.— *Average load-slip traces (solid lines), including plus and minus one standard deviation (broken lines), for adhesive interface metal-plate connector joints subjected to one moisture cycle and (a) constant 12-percent moisture content (MC), (b) moisture cycling between 9- and 15-percent MC, and (c) moisture cycling between 5 - and 19-percent MC.*

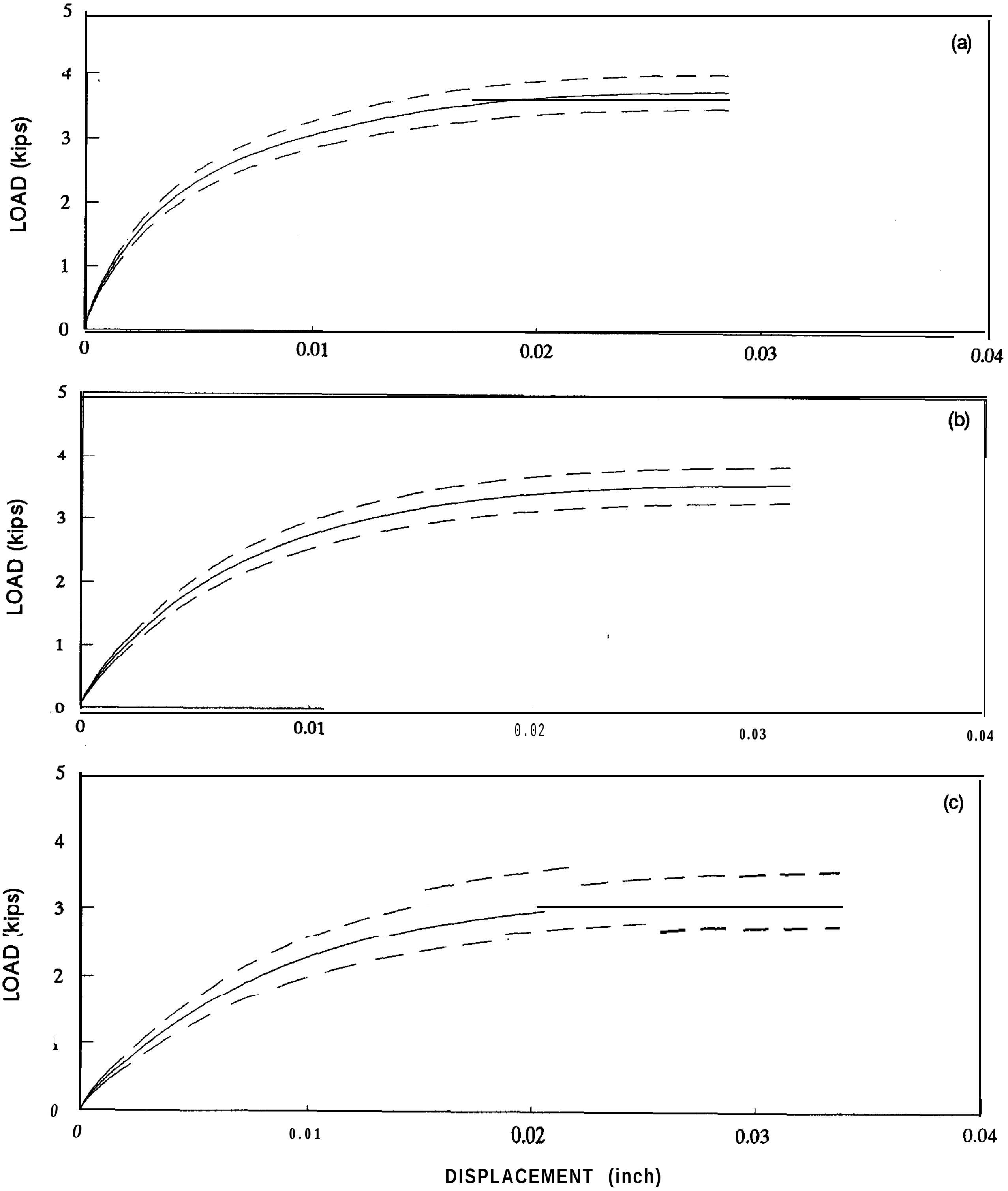

Figure A5.—*Average load-slip traces (solid lines), including plus and minus one standard deviation (broken lines), for standard metal-plate connector joints subjected to two moisture cycles and (a) constant 12-percent moisture content (MC), (b) moisture cycling between 9- and 15-percent MC, and (c) moisture cycling between 5- and Is-percent MC.*

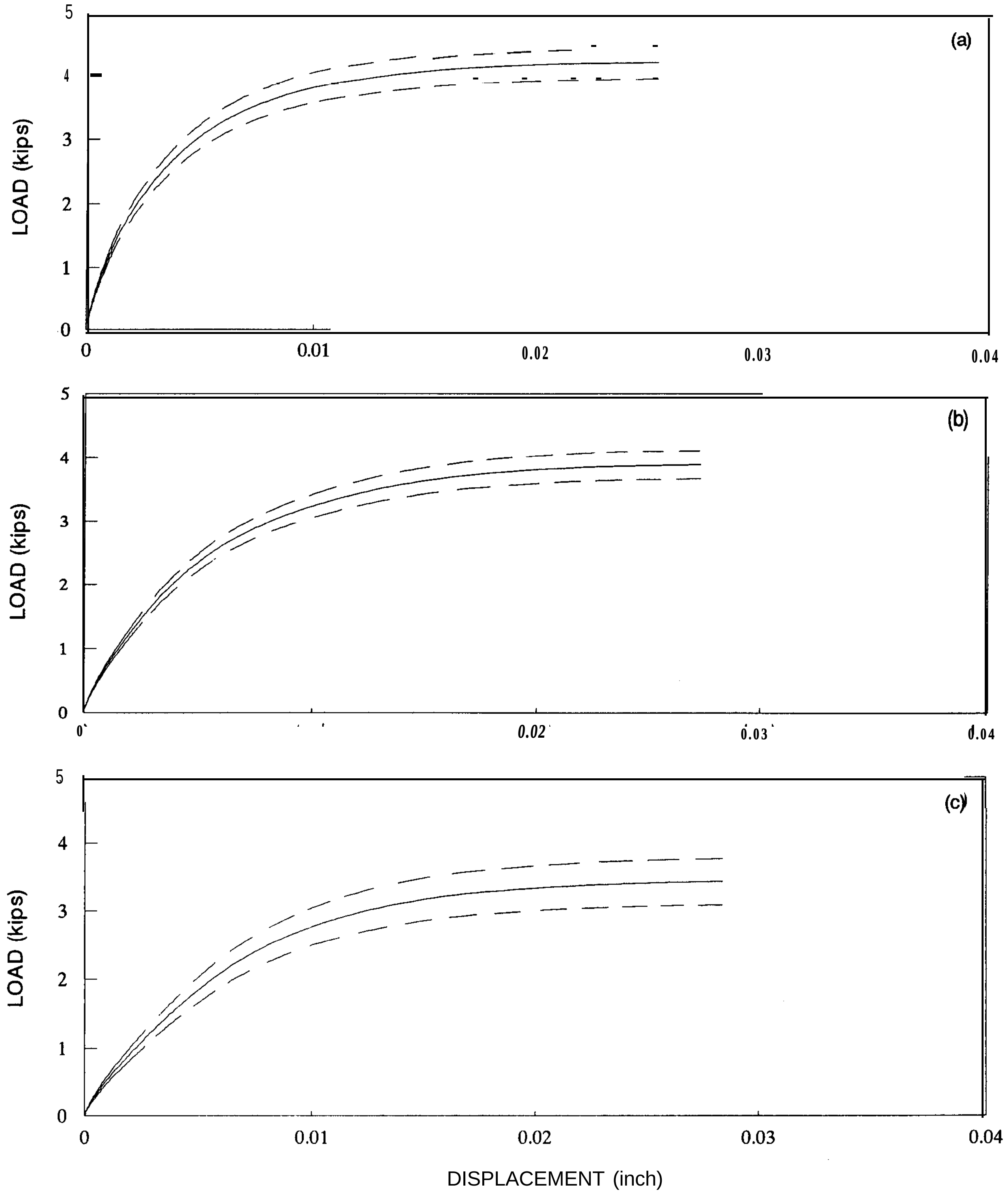

Figure **A6.—** *Average load-slip traces (solid lines), including plus and minus one standard deviation (broken lines), for adhesive interface metal-plate connector joints subjected to two moisture cycles and (a) constant 12-percent moisture content (MC), (b) moisture cycling between 9- and Z-percent MC, and (c) moisture cycling between 5 and 10-percent MC.*

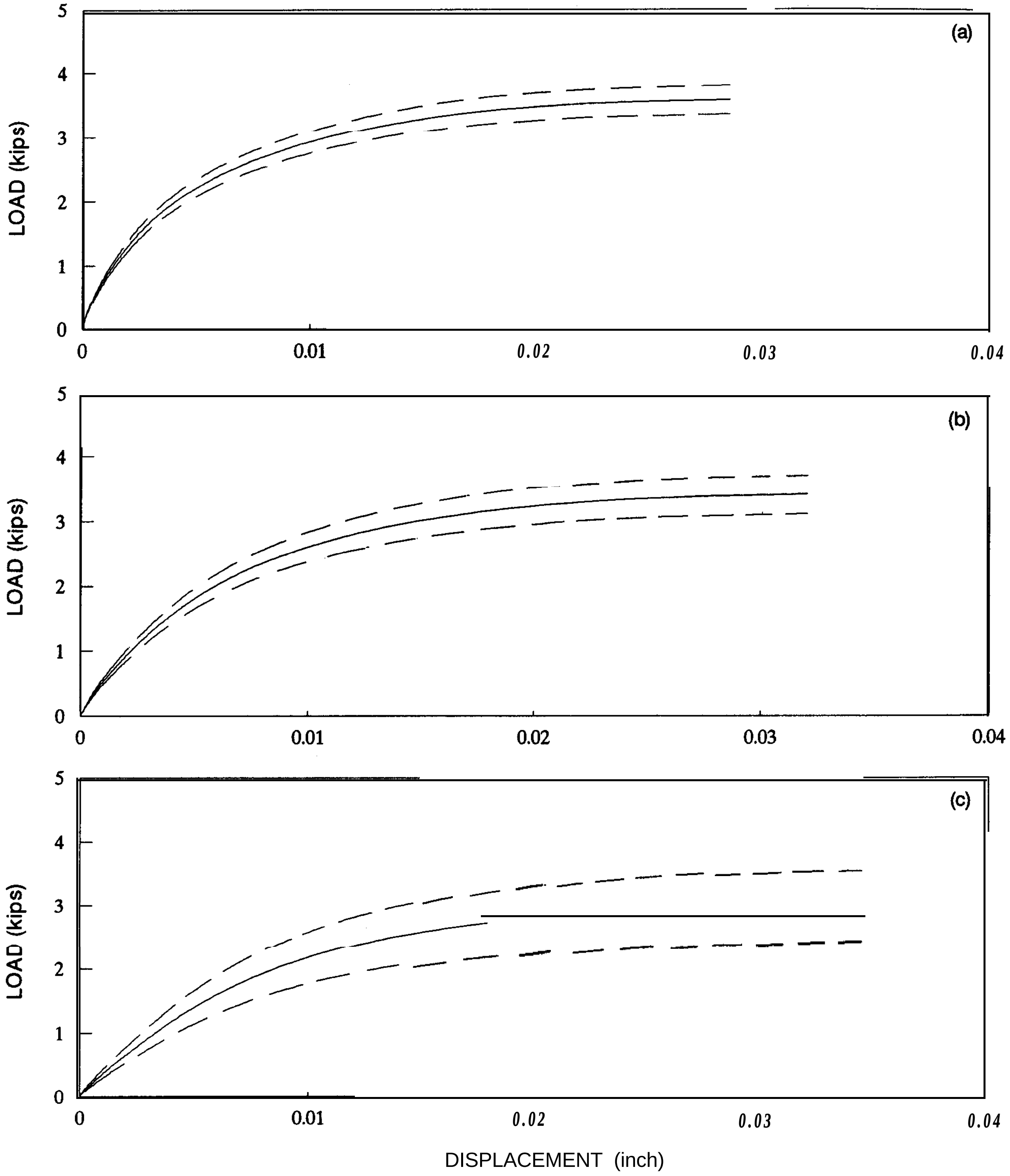

Figure **A7.**— *Average load-slip traces (solid lines), including plus and minus one standard deviation (broken lines), for standard metal-plate connector joints subjected to four moisture cycles and (a) constant 12-percent moisture content (MC), (b) moisture cycling between 9- and 15-percent MC, and (c) moisture cycling between 5- and 19-percent MC.*

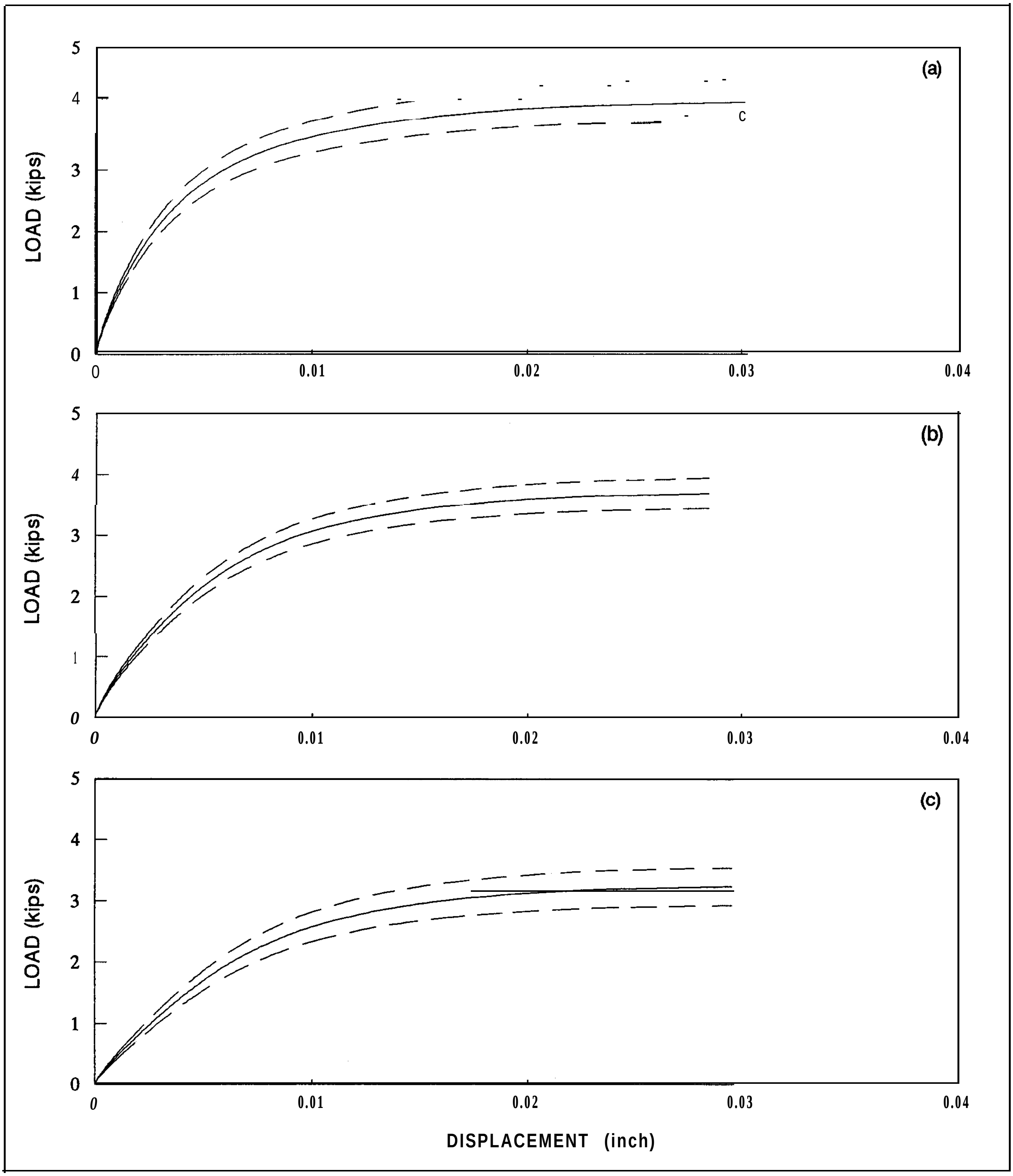

Figure A8.— Average load-slip traces (solid lines), including plus and minus one standard deviation (broken lines), for adhesive interface metal-plate connector joints subjected to four moisture cycles and (a) constant 12-percent moisture content (MC), (b) moisture cycling between 9- and 15-percent MC, and (c) moisture cycling between 5- and 19-percent MC.

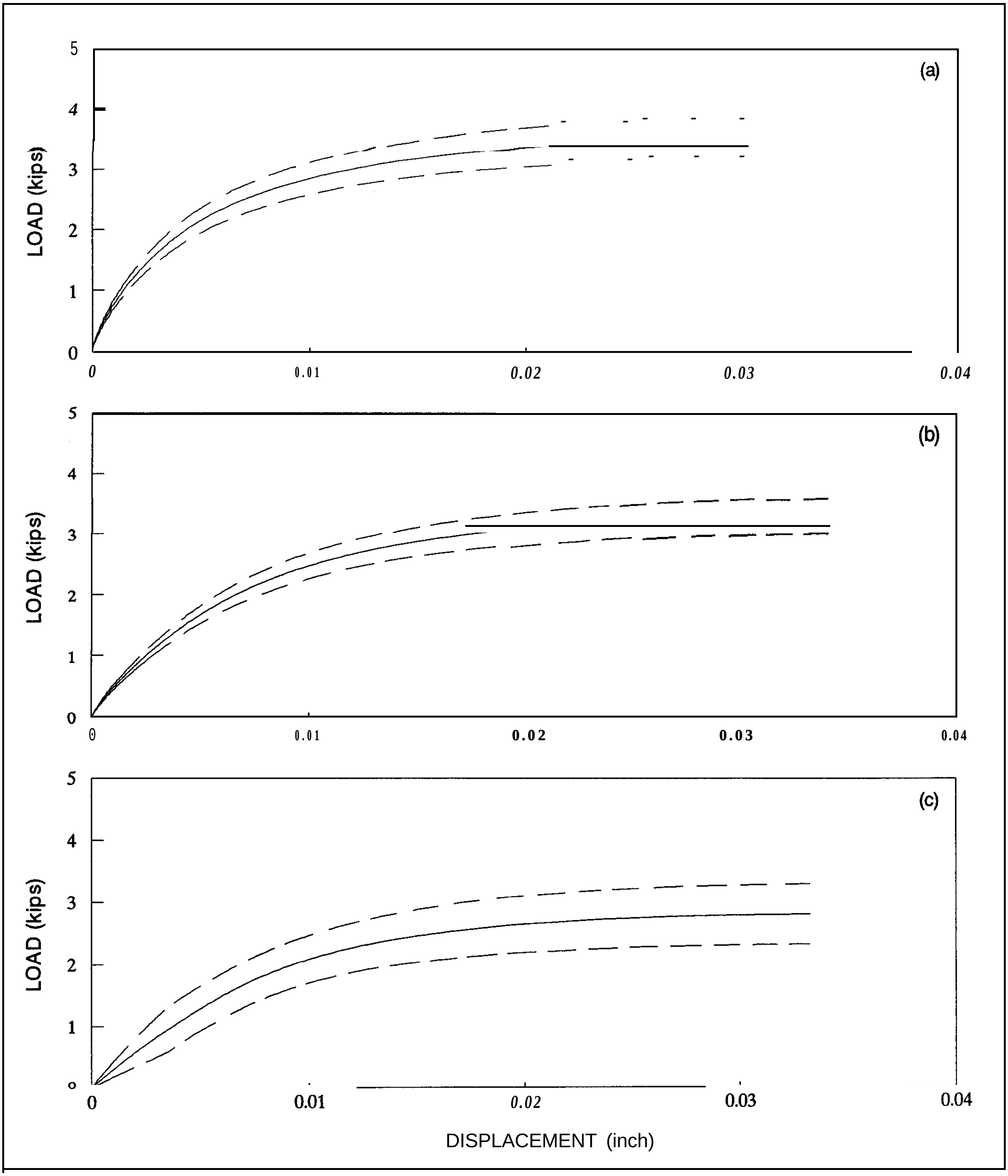

Figure **A9.**— *Average load-slip traces (solid lines), including plus and minus one standard deviation (broken lines), for standard metal-plate connector joints subjected to eight moisture cycles and (a) constant la-percent moisture content (MC), (b) moisture cycling between 9- and 15-percent MC, and (c) moisture cycling between 5- and 19-percent MC.*

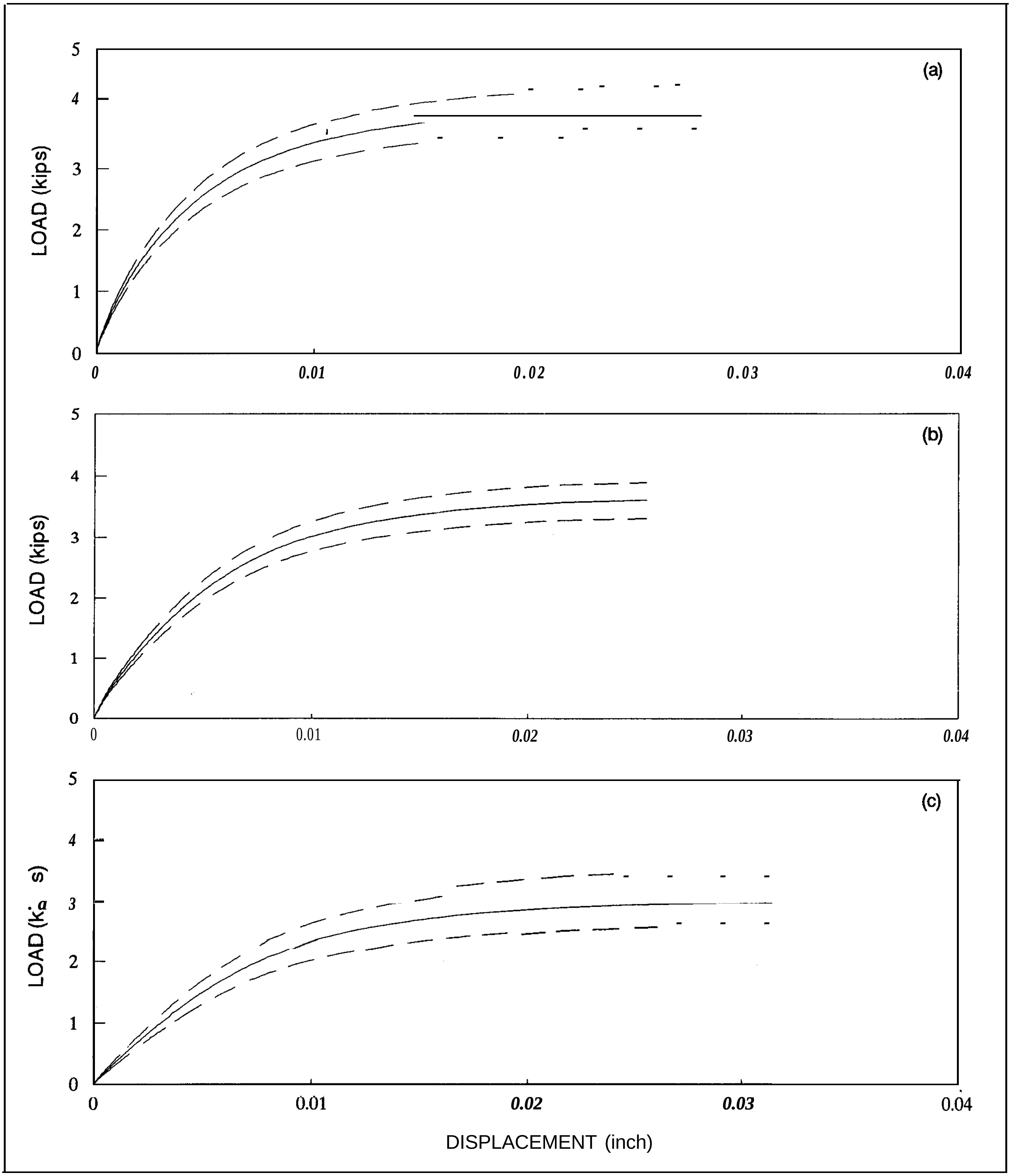

Figure A10.—*Average load-slip traces (solid lines), including plus and minus one standard deviation (broken lines), for adhesive interface metal-plate connector joints subjected to eight moisture cycles and (a) constant 12-percent moisture content (MC), (b) moisture cycling between 9- and 15-percent MC, and (c) moisture cycling between 5- and 19-percent MC.*

Groom, Leslie H. 1995. Effect of moisture cycling on the mechanical response of metal-plate connector joints with and without an adhesive interface. Res. Pap. SO-291. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 27 p.

One hundred and fifty standard metal-plate connector (MPC) joints were constructed and tested in tension to determine the effect of moisture cycling on the mechanical properties of these joints. A similar set of 150 MPC joints was constructed, but these joints were joined with an epoxy adhesive interface between the teeth of the metal plate and wood immediately before joint construction. Both sets of MPC joints were exposed to zero, one, two, four, and eight moisture cycles, with wood moisture contents ranging from 12 percent (constant), 9 to 15 percent, and 5 to 19 percent. The results of the study include the effect of moisture cycling and adhesive interface on physical properties, such as plate backout, and mechanical properties, such as stiffness and strength.

Keywords: Mechanical properties, plate backout, stiffness, truss-plate joints, ultimate load.