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Qualification of the Bar-Lock Rebar Coupler For Use in Nuclear Safety-Related Applications Mechanical Testing Program and Performance Analysis

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Summary

Bechtel Corporation and INEEL developed and performed an independent mechanical testing and analysis program to assess the mechanical performance characteristics of the Bar-Lock L-Series rebar coupler system. A test plan that exceeded the assessment requirements given in ASME Section CC-4333 was developed. To achieve high statistical confidence in measured sample parameters, e.g. ultimate strength, the number of specimens tested was increased to forty (40) from the ASME Code-required quantity of six (6). Bechtel QA/QC personnel monitored the testing program to ensure that it was performed in accordance with the requirements in Specification 24370-C-602.

Static strength tests of two sizes, #6 and #8, of Bar-Lock coupler assemblies showed that they exceeded the ASME-specified minimum strength levels by large margins. Statistical analysis of the results showed a 99.998% probability that the average strength of a group of coupler assemblies would exceed the ASME static strength requirement of 90% of the joined rebar tensile strength. Assessing the performance of individual coupler assemblies against the ASME-specified minimum strength (75 ksi for the Grade 60 rebar used in the tests) for individual assemblies showed that the average strength of an individual assembly was more than 8 standard deviations above the specified minimum. This corresponds to the probability that essentially 100% of all coupler assemblies would exceed the specified minimum strength.

Forty specimens of each of the two sizes (6L and 8L) of coupler/rebar assembly were tested to determine their cyclic loading durability. The test procedure cycled each assembly between 5 and 90% of specified minimum bar yield strength (60 ksi) 100 times. None of the specimens failed in any manner, e.g. bar break, or bar slip within the coupler.

In an effort to improve the cyclic durability performance assessment, several randomly selected specimens received additional cyclic loading. Each selected specimen had an additional 1000 loading cycles imposed. None of the specimens failed, and none of them showed signs of deterioration through excessive strain accumulation or physical deformation. This provides an empirical indication that the cyclic durability of the couplers will far exceed 100 cycles.

Further, some coupler assemblies randomly selected from those already receiving 100 loading cycles were subsequently loaded to failure monotonically (static strength test). This test determined if the prescribed cyclic loading substantially damages the integrity or strength of the coupler splice assembly. The eight specimens tested all achieved the same nominal strength as like specimens receiving no cyclic loading.

The Bechtel/INEEL test program tested and demonstrated that the mechanical properties of the L-Series Bar-Lock mechanical splices meet the existing Codes and NRC requirements and are an acceptable method of connecting reinforcing bar in nuclear power plant safety-related applications. The large quantity of couplers tested provides a higher confidence that the couplers do meet, and indeed far exceed, those ASME-specified requirements.

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Qualification of the Bar-Lock Rebar Coupler for Use in Nuclear Safety-Related Applications: Mechanical Testing Program and Performance Analysis

1. OVERVIEW

Bechtel Corporation and INEEL developed and performed an independent mechanical testing and analysis program to assess the mechanical performance characteristics of the Bar-Lock L-Series rebar coupler system. By design, this program provided a very rigorous test of coupler design mechanical performance, using the qualification criteria of **ASME Section III, Division 2, CC-4333** as a standard of reference.

The Bechtel/INEEL test program tested and demonstrated that the mechanical properties of the L-Series Bar-Lock mechanical splices meet the existing Codes and NRC requirements and are an acceptable method of connecting reinforcing bar in nuclear power plant safety-related applications.

2. TEST PLAN

ASME Section CC-4333 specifies performance criteria to qualify rebar splicing devices for use in nuclear safety-related applications. While the strength specifications are moderately high, the quantity of test specimens required is relatively low. To achieve high statistical confidence in measured sample parameters, e.g. ultimate strength, a larger sample size (n) is required. To achieve the desired level of confidence that any installation of these couplers will have the requisite performance characteristics, the quantity of verification test specimens (the sample set) was increased. For the static strength assessment, the ASME Code requires six specimens be tested, and all six must pass. In this test plan, the quantity was increased to n = 40 for each size tested. For the cyclic durability test, the ASME Code requires three specimens to survive the 100-cycle test. This was increased to n = 40 for each size. Increasing the statistical sample size from six or three to 40 allows a great improvement in the confidence levels (especially for the binomial distribution of the cyclic test) associated with lower bound strength and cyclic durability requirements specified in the Code.

The Bar-Lock testing was monitored by Bechtel QA/QC personnel to ensure that it was performed in accordance with the requirements in **Specification 24370-C-602**.

3. REINFORCING BAR MECHANICAL PROPERTIES TESTS

Mechanical properties for the rebar material used in these tests were determined in accordance with project test procedures, incorporating relevant American Society for Testing and Materials (ASTM) test standards and procedures (**ASTM Designation A 370-96, Standard Test Methods and Definitions for Mechanical Testing of Steel Products**; and **ASTM Designation E 8-99, Standard Test Methods for Tension Testing of Metallic Materials**). All mechanical properties tests were performed on the same universal test machine, using the same measurement transducers. The same test machine, load cell, and extensometer were used in all of the coupler assembly tests as well. Bechtel Quality Assurance Department retains all calibration certification and records for this equipment and these devices.

The reinforcing bar used in the Bar-Lock coupler testing program was ASTM A615 Grade 60 material in #6 (¾ in. nominal diameter) and #8 (1 in. nominal diameter) sizes. Consolidated Power Supply, the vendor of the rebar, provided certified material test reports (CMTRs). The values reported in the CMTRs are based on the results of a single tensile test. The CMTR value, while confirming the nominal material performance, is inadequate to determine "actual" material properties. The ASTM test standard recommends a minimum of three specimens be tested and the results averaged. Additional verification testing was performed as part of this test program to determine the "actual" or measured mechanical properties of the different heats of rebar employed in specimen assembly. Figures 1 and 2 show representative stress-strain curves for both heats of re-bar used in this test program.

3.1 #6 Re-Bar Material

A common heat of rebar (CPS #5898I2899) was used in making up all #6-size coupler test assemblies. Per ASME Section II, Division 2 requirements, the same 10 inch extensometer gage length, as would be used in the #6 coupler assembly tests, was used to measure strain in the tensile properties tests. Seven #6-size plain bar sections from this heat were tested to determine actual tensile properties of this lot of material. Table 1 summarizes the test results. Material properties obtained from Consolidated Power Supply CMTR are provided for comparison.

It is apparent that the differences in yield strength as determined by three different definitions are minimal. For this type of steel, the yield point is the appropriate measurement and provides the most consistent value (smallest standard deviation). Where "measured" or "actual" yield strength is required in the analyses, 67.7 ksi is used for the #6L coupler tests. Where "measured" or "actual" ultimate tensile strength (UTS, or F_u) is required in the analyses, 107.5 ksi is used for the #6 tests.

Table 1. Mechanical Properties of Rebar Used in Test Specimens

	Yield Point (ksi)	0.2%OS Yield (ksi)	0.5% EUL Yield (ksi)	UTS (ksi)	Elongation (%)	E (Msi)
#6 Average	67.7	67.9	68.2	107.5	13.2	27.8
#6 Std Dev	1.03	1.19	1.14	1.12	1.26	0.89
#6 CMTR	--	--	67.6	107.4	15	--
#8 Average	72.6	72.4	72.5	110.1	11.5	29.2
#8 Std Dev	0.45	0.57	0.47	0.74	0.98	0.46
#8 CMTR	--	--	73.1	112.0	14	--
#8 CMTR (C-series only)	--	69.0	--	112.8	16	--

3.2 #8 Re-Bar Material

A common heat of rebar (CPS #5898I3260) was used in making up all of the #8-size coupler test assemblies used in the tensile strength tests. Per ASME requirements, the same 14.5 inch extensometer

gage length was used in the tensile properties test as would be used in the #8 coupler assembly tests. Seven #8-size plain bar sections from this heat were tested to determine actual tensile properties of this lot of material. Table 1 summarizes the results of those tests. Material properties obtained from Consolidated Power Supply CMTR are also provided for comparison. Again, the yield point strength is selected for the material yield strength value. Where "measured" or "actual" yield strength is required in the analyses, 72.6 ksi is used for the #8 tests. Where "measured" or "actual" ultimate strength (UTS) is required in the analyses, 110.1 ksi is used for the #8 tests.

3.3 Material for #8 Coupler Size Cyclic Durability Tests

A separate heat of rebar material (CPS #123741) was used to fabricate the size #8 cyclic test coupler assemblies. There are no measured strength parameters (only specified minimums) associated with the cyclic test procedures, so no verification testing of this material was performed. The CMTR-reported values for this heat are provided at the bottom of Table 1 for reference.

4. DESCRIPTION OF COUPLER TEST SPECIMENS

The Bar-Lock couplers used are Bar-Lock's "L-Series" (coupler designations 6L and 8L), which are higher strength rebar couplers for use in tension/compression, seismic and other cyclic load conditions. The specifications for these couplers are provided in Table 2.

Table 2. Bar-Lock L-Series Coupler Specifications (Sizes #6 and #8)

Coupler Designation	For Use on Rebar Size	Coupler Specifications			Bolt Specifications		
		Outside Diameter (inch)	Length (inch)	Nominal Weight (lbs.)	Quantity per Bar	Size (inch)	Nominal Shear Torque (ft.-lb.)
6L	#6	1.9	8.0	4.5	4	1/2	80
8L	#8	2.2	12.3	9.5	5	5/8	180

The component parts of each Bar-Lock coupler consist of a steel tube, "lock-shear" bolts, and serrated rails. Figure 3 (4-1) shows a schematic diagram of the coupler design. The seamless, hot-rolled steel tube conforms to ASTM A-519, with a minimum tensile strength in excess of 100 ksi. The lockshear bolt material is AISI 41L40. The bolts are through-hardened over the entire bolt length and further induction-hardened at the conical bolt tip. The serrated rails are made of ASTM CD1018. They are machined and then carburized to a depth of 0.032 in.

An equivalent testing program was performed for each of the two coupler/rebar sizes tested. For each size, forty test specimen assemblies were made up for tensile strength tests, and forty assemblies were made up for the cyclic durability tests. The test specimen assemblies were made up by steel construction workers using Bar-Lock's assembly instructions in a normal field environment. Assembly of the test specimens was monitored by Bechtel QC personnel.

5. TEST RESULTS

All of the 160 individual coupler specimens tested in this program, and all relevant specimen sample set averages and individual coupler strengths, exceeded the requirements set forth in the ASME Code, Section CC-4333.2.3(a).

Eighty tensile strength tests (forty of each size) were performed on coupler assembly specimens according to relevant sections of ASTM A 370 and E 8, and ASME CC-4333.2.3(a). A representative stress-strain curve for a coupler strength test is provided in Figure 4 (Fig 3 in Appendix E). No practical differences were observed in the general character of the stress-strain curve of any of the 80 specimens tested. All test data collected included stress, strain, crosshead displacement, applied force, and elapsed time. The actual individual test specimen results obtained through standard analysis methods provided in ASTM E 8 are tabulated in Tables 3 and 4. A representative stress-strain plot for a cyclic test is provided in Figure 5.

Table 3. Tensile Properties for #6 Rebar (Heat ID: 5898I2899)

Specimen ID	HOF Yield (ksi)	UTS (ksi)	?$_f$ (%)	E (Msi)
U6-2	67.7	106.9	14.0	28.7
U6-5	66.8	106.6	13.5	27.4
U6-9	67.0	107.0	12.9	28.1
U6-11	67.6	107.8	14.2	28.6
U6-12	69.9	109.7	10.6	27.3
U6-14	67.9	107.9	12.9	28.3
U6-18	67.3	106.5	14.1	26.2
Averages	67.7	107.5	13.2	27.8

Table 4. Tensile Properties for #6 Rebar Heat ID: 5898I2899

Specimen ID	HOF Yield (ksi)	UTS (ksi)	?$_f$ (%)	E (Msi)
U8-11	72.5	110.3	12.9	30.1
U8-12	72.4	108.8	11.2	28.7
U8-13	71.7	109.5	12.2	29.3
U8-14	73.0	111.0	9.8	28.8
U8-16	72.8	110.2	11.0	29.1
U8-18	72.5	110.4	11.7	29.2
U8-20	73.0	110.6	11.5	29.1
Averages	72.6	110.1	11.5	29.2

In addition, several specimens of each size were randomly selected to receive an initial slip test prior to the normal strength test. A statistically-legitimate random selection process, using a random number generation algorithm on a computer, was applied to make the selections. Virgin test specimens were installed in the test machine, and instrumented as for a normal strength test. The applied stress was increased from 0, through 3 ksi, up to 30 ksi, and then reduced to 3 ksi. The change in displacement across the coupler between the two 3 ksi stress levels was measured with an extensometer. Figure 5 shows the traces of applied stress and resultant displacement for the six specimens. In all cases, no measurable slip was detected.[1] The observation of no bar slip within the coupler on initial loading means the coupler will develop full strength without excessive deformation upon initial loading.

5.1 Tensile Test Results

The ASME Code, Section CC-4333.2.3, has several criteria with which coupler performance is compared. The two pertinent criteria for the tensile strength test results are:

1. "…The *average tensile strength*[2] of the splices shall not be less than 90% of the actual tensile strength of the reinforcing bar being tested, nor less than 100% of the specified minimum tensile strength."

2. "…The *tensile strength of an individual splice system* (test specimen)[3] shall not be less than 125% of the specified minimum yield strength of the spliced bar."

The coupler assembly performance for both sizes evaluated exceeded both of these criteria. Table 5 tabulates the results of the individual strength tests. Discussion of the comparisons of test results to ASME specified minimum values follow:

5.1.1 Minimum Average Tensile Strength Comparison

For the lots of rebar tested, the "90% of the actual tensile strength" is the governing criteria. For the size #6 group, the specified minimum average strength value is 96.8 ksi. For the size #8 group, the specified minimum average strength value is 99.1 ksi.

5.1.1.1 Coupler/bar size #6

The sample set of strength data from the coupler/bar size #6 was evaluated for normal (Gaussian) probability distribution using the Wilk-Shapiro W-test and graphical analysis methods. The results show a near normal distribution, i.e. only slight departure from normality. Where necessary in the assignment of confidence limits, the assumption of normality is justified.

The size #6 group (sample set, n = 40) average tensile strength is 106.2 ksi (98.8% of the average #6 bar actual tensile strength), with a standard deviation of only 1.87 ksi. The Code-

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[1] the measured slip displacements, equivalent to less than 0.001 in. over the length of the coupler, were much less than observed hysteresis error in the extensometer.

[2] This is a single average value, calculated from the entire group (sample set) of replicate test specimens, i.e. from one heat of material, in one size.

[3] This is the strength value of each individual test specimen (coupler assembly) consisting of one coupler unit and two attached sections of rebar.

required average strength value of 96.8 ksi (90% of actual tensile strength) is 5.0 standard deviations below the sample average. This corresponds to a probability of less than 3 in 10 million couplers would have strength less than the required 96.8 ksi minimum value. Further, a one-sided test for lower bound was also performed. This test provides a practical lower limit strength value for any #6L coupler assembly. Based upon this data set 99% of all couplers of this type will have a tensile strength greater than 100.13 ksi (with a 99% confidence level). This is a very strong indication that the size #6 coupler design will achieve the required minimum strength. These results are confirmed in a letter report (see Appendix F) from INEEL statistician J.J. Einerson. Mr. Einerson reviewed the statistical analyses of the mechanical test data.

5.1.1.2 Coupler/bar size #8

The sample set of strength data from the coupler/bar size #8 was also evaluated for normal (Gaussian) probability distribution using the W-test and graphical analysis methods. Again, results show only slight departure from normality.

The size #8 group (sample set, n = 40) average tensile strength is 109.0 ksi (99.0% of the average #8 bar actual tensile strength), with a standard deviation of only 2.78 ksi. The required average strength value of 99.1 ksi is 3.6 standard deviations below the sample average. This corresponds to a probability of less than 2 in 10,000 couplers would have a strength less than the required 99.1 ksi minimum value. Further, the one-sided test for lower bound (described above) based upon this data set indicates that, with 99% confidence, 99% of all couplers of this type will have a tensile strength greater than 99.94 ksi (see letter report included in the Appendix). This is a very strong indication that the size #8 coupler design will achieve the required minimum strength.

To assess the general capabilities of the overall coupler design, the results from both sizes tested can be normalized by their respective bar lot (mill heat) tensile strengths and combined into one sample set. In so doing, the conclusion is that the Bar-Lock coupler design produces a splice that will achieve an average strength that is 98.9% as strong as the rebar itself. It is obvious that this greatly exceeds the ASME Code-required 90% value. The cumulative standard deviation is 2.2% of the bar strength, making the required minimum strength 4.0 standard deviations below the sample average. The equivalent likelihood is that only 3 in 100,000 would fail to achieve a strength level equivalent to 90% of the bar ultimate strength.

5.1.2 Minimum Tensile Strength of Individual Specimens

This requirement for each individual coupler tested provides additional assurance that the occasional sample tested that may have a relatively low strength value, as compared to the sample set average, at least has an absolute minimum necessary strength for structural considerations. For the Grade 60 rebar used in this study, this required value is 75.0 ksi, and is the same for all specimens tested. All specimens tested in this test program passed this test, and by a very large margin.

5.1.2.1 Binomial (Pass/Fail) Assessment

In the simplest case, the pass/fail criteria can be applied directly. For the combined sample size of 80, with no observed failures (strength below 75.0 ksi), the statement can be made that with 90% confidence, no more than 2.8% of couplers would fail this test. By the nature of this type of binomial probability distribution (pass/fail), it is difficult to state reliabilities with

a higher level of confidence without assessing many hundreds of samples. However, by normalizing the measured individual coupler strengths by the required value, an analysis of the amount of deviation on those values can provide a yet stronger comparison and corresponding statement of reliability.

5.1.2.2 Assessment Using Normalized Coupler Strength Distribution

This distribution of normalized strengths shows that the average coupler strength is 144% of the minimum required level for individual couplers, with a standard deviation of less than 4%. So the required strength value is 11 standard deviations below the sample average. The probability tables do not show probabilities below 8 standard deviations from the mean, but at that value, the probability is less than 2x10-15 that the strength of an individual assembly would be lower than the requirement, i.e. practically impossible.

5.1.2.3 Assessment Using Alternative Strength Criterion

A comment by the US Nuclear Regulatory Commission (USNRC), during a presentation on the Bar-Lock couplers on August 9, 2001, was that the minimum strength criterion for individual test specimens should be based upon the actual, measured yield strength of the bar material, rather than the specified minimum value (as done above, per the ASME qualification specification). This makes more sense from a practical view, and it removes one variable (the specified material yield strength) from the comparison. However, this approach does apply a more stringent test of the coupler capability, since the actual yield strength will always be higher than the minimum allowable. To apply this criterion, the size #6 and size #8 specimens must be treated separately since the measured yield strengths of the two bar sizes are significantly different.

<u>Size #6 Couplers</u>

Using the appropriately normalized test results from the #6 test specimens, the same analysis described above was carried out. The size #6 coupler specimen tensile strengths averaged 106.2 ksi, 25.4% above the USNRC-proposed strength level of 84.6 ksi (125% * 67.7 ksi) with a standard deviation of 1.86 ksi. The proposed minimum strength here is still more than 11 standard deviations above the proposed minimum level, with the probability being essentially zero that any coupler would fail to achieve this strength level.

<u>Size #8 Couplers</u>

Analyzing the normalized test results from the #8 test specimens show their tensile strengths averaged 109.0, 20.1% above the USNRC-proposed strength level of 90.8 ksi (125% * 72.6 ksi) with a standard deviation of 2.81 ksi. The proposed minimum strength here is still 6.5 standard deviations above the proposed minimum level. The resultant failure probability is still less than 1x10-10.

5.1.3 Tensile Strength Performance Exceeds Requirements

The overall strength performance of the Bar-Lock coupler design can be summarized as excellent, based on this comprehensive test program of different size couplers. There were no failures to meet any of the specified or proposed strength criteria in any case. As the various failure probability values indicate, the likelihood of any individual Type 6L or 8L coupler assembly failing to achieve the ASME required strength levels is very low.

Table 5. Re-Bar Splice Assemblies Strength Test Results

Specimen ID (#6)	Failure Type[4]	Final Strain (%)	UTS (ksi)	Specimen ID (#8)	Failure Type	Final Strain (%)	UTS (ksi)
Average	--	NA[5]	106.2	Average	--	NA[b]	109.0
S6-01	O	3.8	107.9	S8-01	O	3.7	109.6
S6-02	P	15.2	108.0	S8-02	T	1.4	96.8
S6-03	P	14.4	98.9	S8-03	O	4.9	109.8
S6-04	P	15.2	106.4	S8-04	O	3.7	110.1
S6-05	O	4.9	107.3	S8-05	P	10.4	108.4
S6-06	O	4.1	107.8	S8-06	T	4.9	109.7
S6-07	O	4.2	107.6	S8-07	T	4.4	110.4
S6-08	P	13.1	106.9	S8-08	T	3.6	109.4
S6-09	T	2.7	103.2	S8-09	O	3.6	110.5
S6-10	O	4.6	107.6	S8-10	T	1.8	102.1
S6-11	P	13.0	107.3	S8-11	T	2.1	106.0
S6-12	O	4.4	105.6	S8-12	*	3.8	108.0
S6-13	T	2.7	103.4	S8-13	O	3.4	110.5
S6-14	P	10.8	105.8	S8-14	T	3.2	110.1
S6-15	P	12.3	104.0	S8-15	*	3.7	106.7
S6-16	O	3.8	108.0	S8-16	T	4.0	111.0
S6-17	P	9.8	103.7	S8-17	T	2.1	104.5
S6-18	P	11.5	106.3	S8-18	T	4.5	109.3
S6-19	P	19.1	106.1	S8-19	T	4.0	109.4
S6-20	P	15.4	107.6	S8-20	O	4.6	110.1
S6-21	P	11.0	106.0	S8-21	T	3.5	109.7
S6-22	P	11.6	105.0	S8-22	T	4.3	109.4
S6-23	T	2.7	103.1	S8-23	T	3.8	109.8
S6-24	O	4.1	107.8	S8-24	T	3.3	108.5

[4] B = bar break outside coupler but within extensometer gage length, O = bar break outside coupler and outside extensometer gage length, T = bar break at tip of first lock bolt, P = bar pulled out of coupler without breaking, * = bar break in interior of coupler

[5] The final strain is dependent on several factors, including mode of failure. An average value for all tests has no significance. For example, in a pull-out failure the final strain is determined by the length of time the operator chooses to continue the test once pull-out is observed.

Specimen ID (#6)	Failure Type[4]	Final Strain (%)	UTS (ksi)	Specimen ID (#8)	Failure Type	Final Strain (%)	UTS (ksi)
Average	--	NA[5]	106.2	Average	--	NA[b]	109.0
S6-25	P	11.5	105.1	S8-25	P	10.4	110.0
S6-26	P	11.3	107.9	S8-26	T	4.2	109.9
S6-27	P	12.2	106.4	S8-27	*P	7.0	109.7
S6-28	O	3.9	107.8	S8-28	T	4.1	109.0
S6-29	B	4.8	107.0	S8-29	O	3.8	109.7
S6-30	O	4.3	107.6	S8-30	O	3.5	110.3
S6-31	O	4.4	107.4	S8-31	T	3.9	110.5
S6-32	T	3.8	107.2	S8-32	T	2.5	109.0
S6-33	T	2.9	105.7	S8-33	O	4.4	110.3
S6-34	P	12.6	105.7	S8-34	T	3.5	109.7
S6-35	T	4.4	107.2	S8-35	T	2.5	105.4
S6-36	T	2.8	104.2	S8-36	T	4.1	110.5
S6-37	O	3.8	107.2	S8-37	*	5.0	110.2
S6-38	P	11.5	107.4	S8-38	P	10.3	109.9
S6-39	P	12.9	107.0	S8-39	T	3.9	111.2
S6-40	P	11.3	106.3	S8-40	P	10.2	113.6

5.2 Cyclic Test Results

Coupler assemblies were cyclically tested according to the requirements of ASME CC-4333.2.3(b). Forty specimens of each of the two types (6L and 8L) received 100 load cycles between 5 and 90% of specified minimum bar yield strength (60 ksi). None of the specimens failed in any manner, e.g. bar break, or bar slip within the coupler.

Applied stress and specimen extension data were digitized during the cyclic tests to provided additional insight into the coupler performance under cyclic load conditions. Figure 6 shows a representative plot of stress versus displacement. For clarity, only every tenth cycle is presented. It shows the accumulated slip over 100 cycles to be less than 0.0015 in. This is less than 10% of the elastic deformation that occurs during a single load cycle. The same behavior was observed in all of the tests of both coupler sizes. The couplers showed no significant deterioration (visible, or evidenced by deviation is test data) during the tests.

Based on the binomial probability function (pass/fail testing), and no observed failures in 80 tests, it can be stated with 90% confidence that less than 2.8% of all couplers would fail prior to the completion of 100 loading cycles.

5.2.1 Higher Count Cyclic Tests

In an effort to improve the cyclic durability performance assessment, several of the specimens in each size were selected at random to receive additional cyclic loading. Each selected specimen was subjected to an additional 1000 cycles. None of the specimens failed, and none of them showed signs of deterioration through excessive strain accumulation or physical deformation. While this does not provide a verifiable improvement in the statistical probability of failure (the confidence level is too low to be useful), it does provide an engineering indication that the cyclic durability of the couplers will far exceed 100 cycles.

5.2.2 Residual Strength Tests

Another test was also performed on randomly selected couplers to provide additional information regarding cyclic durability and residual strength. The selected couplers, all having been subjected to 100 loading cycles, were subsequently loaded to failure monotonically. This is the standard "tensile strength test" described in the previous section. The concept here is to determine if the prescribed cyclic loading substantially damages the integrity of the splice assembly. The eight specimens tested all achieved the same nominal strength as the corresponding specimens receiving no cyclic loading. Table 6 summarizes these test results. These observations suggest that cyclic loading in the stress range from 3 to 54 ksi does very little, if anything, to reduce the strength capacity of a spliced joint made using the Bar-Lock L-series coupler.

Table 6. Results of Residual Strength Tests on Load-Cycled Specimen Assemblies

Specimen ID (#6)	Failure Type	Final Strain (%)	UTS (ksi)	Specimen ID (#8)	Failure Type	Final Strain (%)	UTS (ksi)
Average	--	NA	104.9	Average	--	NA	106.7
C6-2	P	3.8	104.3	C8-15			106.6
C6-3	P	3.7	106.3	C8-21			106.0
C6-7	P	5.0	106.2	C8-27			107.6
C6-14	P	7.0	103.3				
C6-15	P	3.7	104.5				

6. COUPLER TEST PROGRAM CONCLUSIONS

The Bar-Lock coupler qualification testing program was carried out on two representative sizes – #6 and #8 – of their L-Series couplers. One hundred-sixty (160) coupler assemblies were tested. Fourteen (14) pieces of plain rebar were tested to determine the actual, or measured, mechanical properties of the two heats of bar material used in the test specimens.

6.1 Tensile Strength

The tensile strength tests on 80 samples from each of the two sizes all exceeded the two ASME requirements by a large margin. Statistical analyses of the test results determined several important performance indicators, all of which suggested that any given coupler assembly would far exceed the

ASME-specified strength requirements. *The overall probability of any coupler assembly (in size #6 or #8) failing to meet the minimum qualification strength criterion is less than* **3 in 100,000**.

There was some variation in strength between the two heats of rebar used in the strength tests. Comparing and correlating these results show that Bar-Lock L-Series coupler splices can be expected to achieve a tensile strength greater than 96% of the actual strength of the bar material that is connected using the coupler device. While there are not enough different combinations of bar material and coupler size data to make this statement with high probabilistic certainty, the combined test results from this program appear similar when normalized by the actual bar strength. Therefore, it is likely these test results are representative of the performance of other sizes of Bar-Lock L-Series couplers. In other words, the mechanical design of the Bar-Lock L-Series coupler is such that spliced joints can be expected to develop over 96% of the actual bar strength.

6.2 Mechanical Slippage in the Couplers

Slip tests performed on selected specimens of both sizes showed a solid mechanical connection between the coupler and the rebar. There was no tendency for the rebar to move within the coupler prior to developing full splice strength. This was expected since the conical-tipped lock bolts physically embed into the bar material providing a physical shear force transfer from bar to coupler.

6.3 Cyclic Loading Durability

All 80 splice specimens that underwent the cyclic loading durability test passed the 100-cycle test, with no obvious physical degradation of the spliced joint. To provide an additional degree of assurance of adequate cyclic durability, selected specimens received 1000 cycles of loading, again with no noticeable physical degradation. Some of the specimens that passed the 100 cycle test were subsequently tested by monotonic loading to failure. The resultant measured strengths were essentially the same as the virgin strength test specimens (no cyclic loading applied). These results suggest that the design of the Bar-Lock coupler is essentially insensitive to cyclic loading to levels below 90% of the minimum bar yield strength.

6.4 Overall Coupler Performance

All of these test results, compared to the ASME splice system qualification requirements, indicate that the Bar-Lock coupler design for rebar splicing is entirely adequate from a strength point of view for use in nuclear safety-related construction. The large quantity of couplers tested provides higher confidence that the couplers do meet, and indeed far exceed, those ASME-specified requirement.

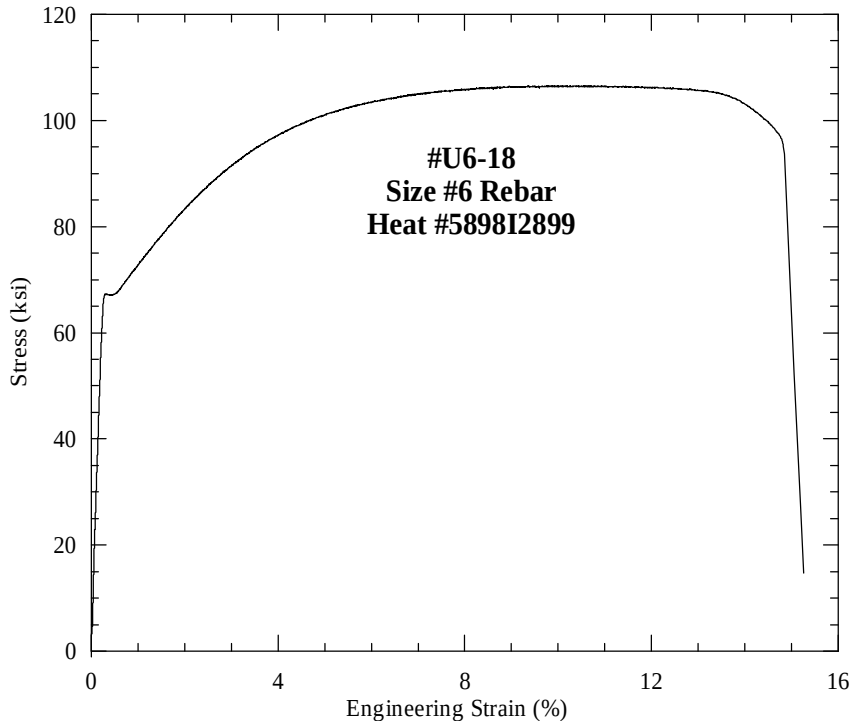

Figure 1. Representative Stress-Strain Curve from #6 Rebar Material

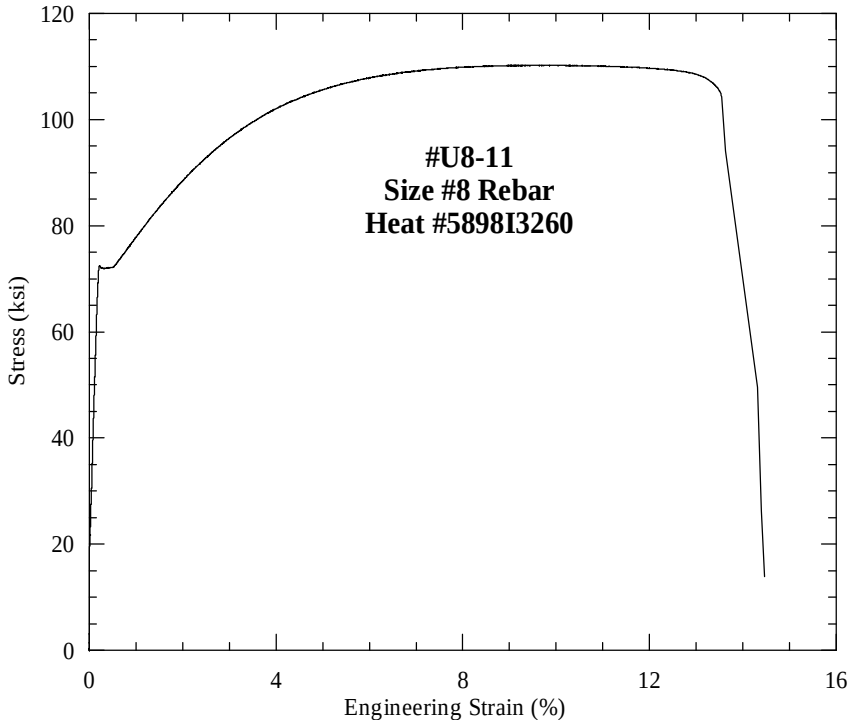

Figure 2. Representative Stress-Strain Curve from #8 Rebar Material

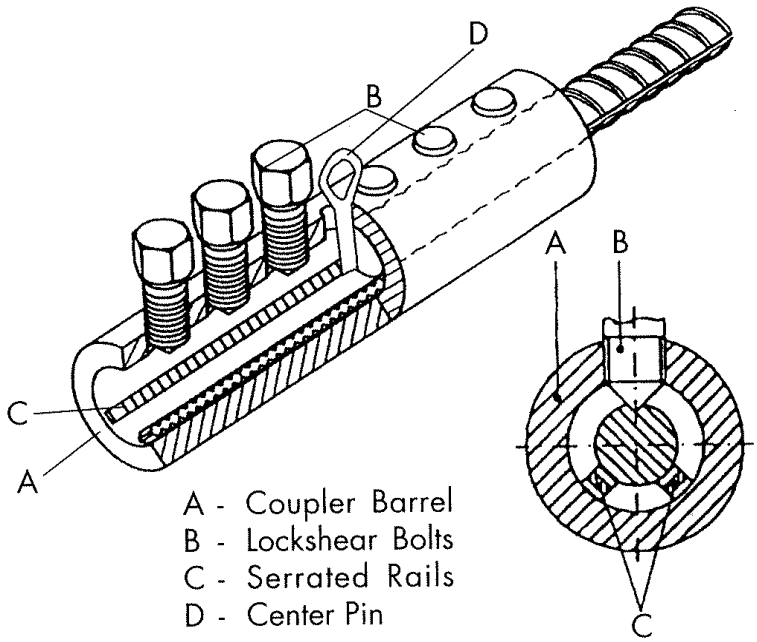

Figure 3. Bar-Lock Coupler Cutaway View Showing Internal Details

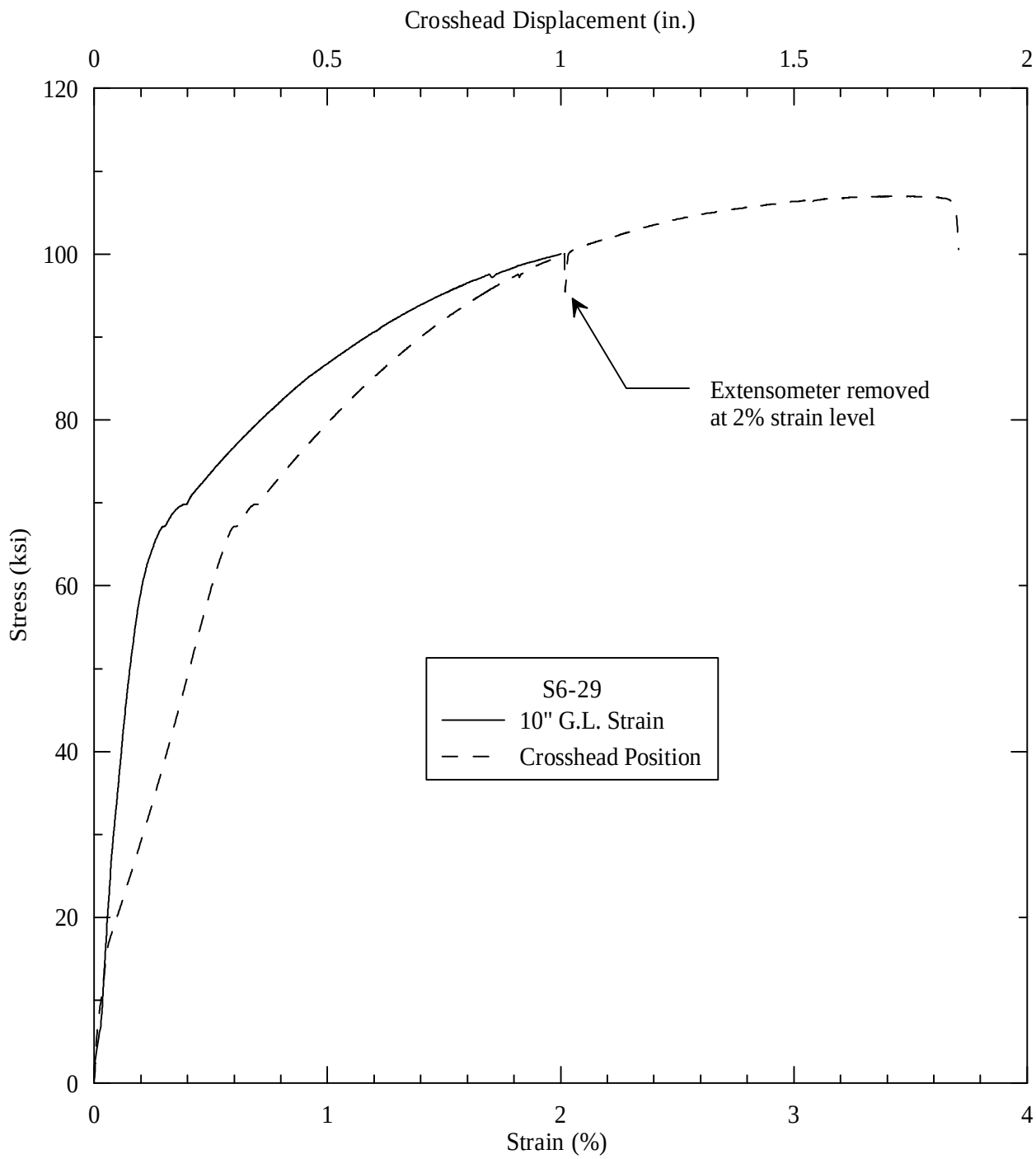

Figure 4. Representative Test Data from a Coupler Assembly Strength Test

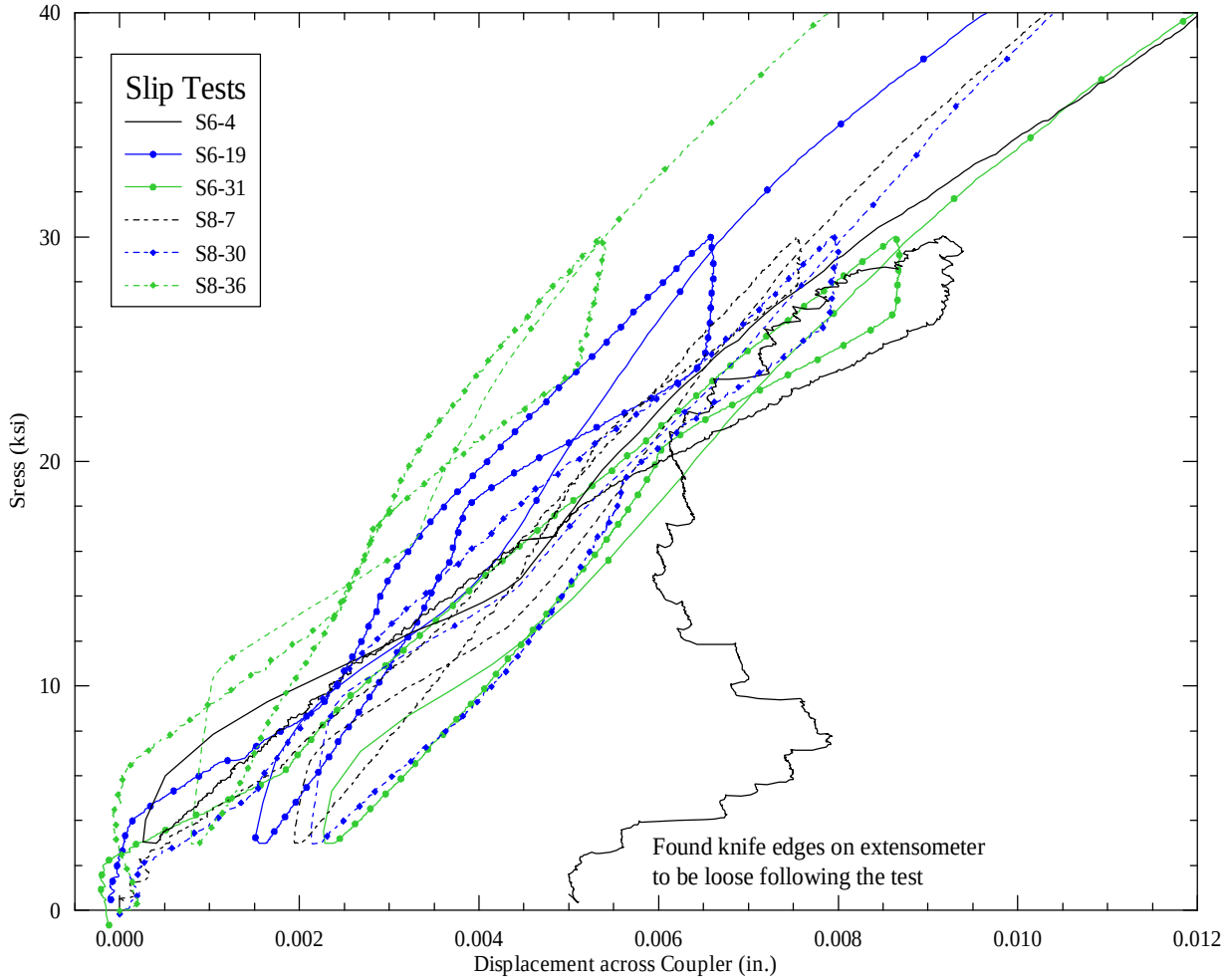

Figure 5. Data Curves Showing Load-Unload Cycle to Assess Bar Slip in Couplers

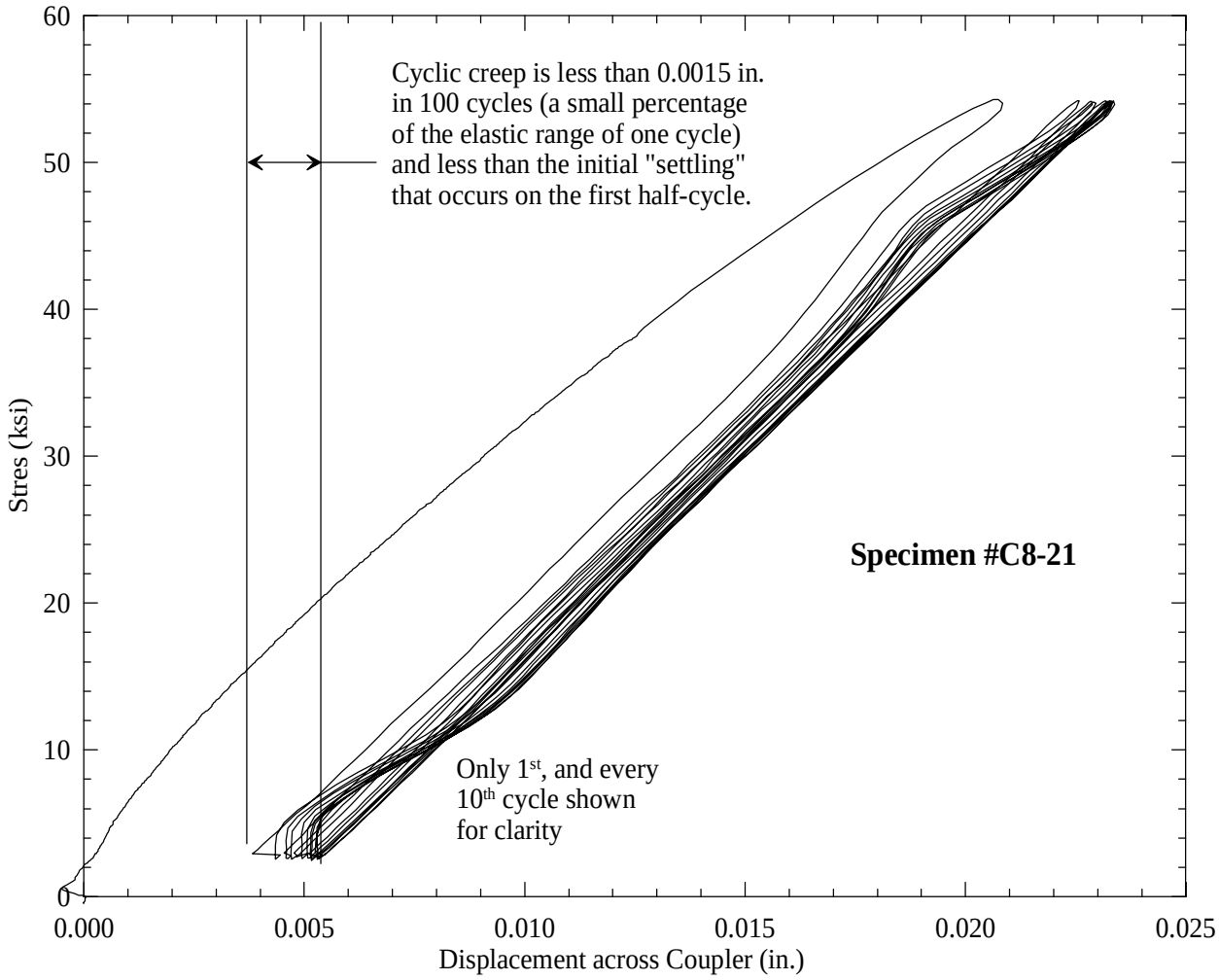

Figure 6. Cyclic Stress-Displacement History for a Typical Test