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CYCLIC MATERIAL PROPERTIES TESTS SUPPORTING ELASTIC-PLASTIC ANALYSIS DEVELOPMENT

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ABSTRACT

Correlation studies have shown that hardening models currently available in the ABAQUS finite element code (isotropic, kinematic) do not accurately capture the inelastic strain reversals that occur due to structural rebounding from a rapidly applied transient dynamic load. The purpose of the Cyclic Material Properties Test program was to obtain response data for the first several cycles of inelastic strain reversal from a cyclic properties test. This data is needed to develop elastic-plastic analysis methods that can accurately predict strains and permanent sets in structures due to rapidly applied transient dynamic loading. Test specimens were cycled at inelastic strain levels typical of rapidly applied transient dynamic analyses (0.5% to 4.0%). In addition to the inelastic response data, cyclic material properties for high yield strength (80 ksi) steel were determined including a cyclic stress-strain curve for a stabilized specimen.

Two test methods, the Incremental Step Method and the Companion Specimen Method, were used to determine cyclic properties. The incrementally decreasing strain amplitudes in the first loading block of the Incremental Step Method test is representative of the response of structures subjected to rapidly applied transient dynamic loads. The inelastic strain history data generated by this test program will be used to support development of a material model that can accurately predict inelastic material behavior including inelastic strain reversals. Additionally, this data can be used to verify material model enhancements to elastic-plastic finite element analysis codes.

BACKGROUND

The primary objective of this test program was to obtain response data for the first several cycles of inelastic strain reversal from a cyclic properties test.

This test program subjected high yield strength steel specimens to alternating tension and compression loads that strained the specimens to pre-defined inelastic strain levels. Standard (full-size) hour glass specimens with straight sided collet grips (Reference (1)) were fabricated from 1.00 inch thick high yield strength steel plate. Test data was recorded in digital form and used to create a cyclic stress-strain curve for high yield strength steel.

This test program supported development of elastic-plastic analysis methods which require inelastic material properties for high yield strength steel that accurately account for the effects of strain reversal in order to predict strains and permanent set in structures that undergo rapidly applied transient dynamic loading.

The cyclic stress-strain curve, obtained by cycling a material specimen between alternating loads of tension and compression, can be notably different from the monotonic stress-strain curve, traditionally obtained from a near-static tensile loading condition. The cyclic stress-strain curve provides a measure of the steady-state cyclic deformation resistance of a material. The two methods used to determine the cyclic stress-strain curve, the Incremental Step Test and the Companion Specimen Test, are discussed below.

INCREMENTAL STEP TEST

The Incremental Step Test subjected a specimen to blocks of cycles in which the strain amplitude incrementally decreased from a predetermined maximum strain value. In Reference (2), this method was proven to be an expedient way of generating the cyclic stress-strain curve. After several blocks of these incremental strain cycles, depending on the maximum strain value, the material cyclically stabilizes. In addition, the pattern of incrementally decreasing strain cycles in the first loading block is representative of the dynamic response of an unstrained structure when subjected to a rapidly applied transient dynamic load.

Continuously plotting the stress versus strain data throughout an incremental strain block generates a series of superimposed hysteresis loops. The cyclic stress-strain curve for a particular block can be formed by connecting the tips of the superimposed hysteresis loops. The initial cycle of each block subjected the specimen to the maximum strain amplitude required by the test for that test specimen. The remaining strain amplitudes in the block decreased by increments of one-fifteenth of the maximum strain amplitude. The pattern of incrementally decreasing strain amplitude blocks continued until stabilization or failure occurred. A zero strain increment approximately two seconds long was inserted between each loading block.

Using this method, the initial loading of the test represents the monotonic stress-strain curve of the material up to the maximum strain level for the test. The cyclic hardening or softening characteristics of the material can be determined by comparison of the cyclic stress-strain curve created using the first block of data compared to the stress-strain curve generated using the stabilized block of data.

A form of the incremental step test described in Reference (2) was used to generate the required stress-strain curves for this cyclic test application, based on the following assumptions:

- The cyclic stress-strain curve can be generated using a single specimen, and
- A relatively few number of blocks of strain cycles at the specified strain amplitudes are required to attain a stable state of strain within the specimen.

A typical transient strain response to a rapidly applied transient dynamic load resembles a damped sinusoidal wave that decays with time. This pattern of straining is approximated by the gradually decreasing strain amplitude in the initial input block of the Incremental Step Test. Because of the type of strain response resulting from a rapidly applied transient dynamic load and its applicability to this test series, the strain input for the Incremental Step Test, indicated in Figure 1, was used.

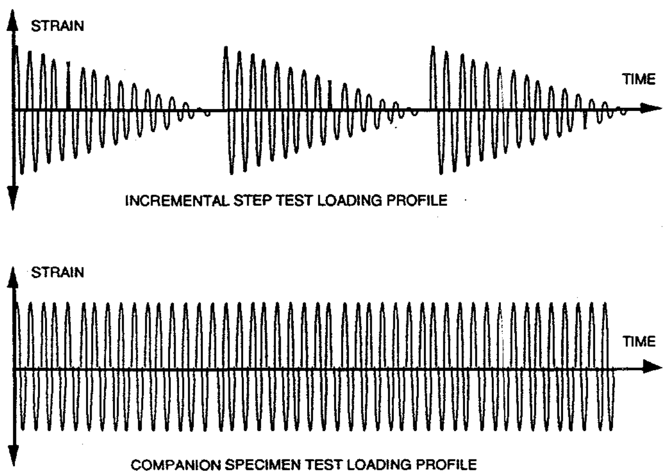

Figure 1 Comparison of Loading Profiles for Cyclic Testing

The number of blocks required to reach a steady state is inversely proportional to the number of cycles per block. A test procedure with more cycles per block requires fewer blocks to reach stabilization. For an input block containing cycles of both increasing and decreasing strain amplitudes, Reference (2) recommends between 20 and 30 cycles per block. To remain consistent with this requirement, the recommended procedure for this test used input blocks containing 15 cycles of decreasing strain amplitude only. This also appears to agree with the sample cyclic test data supplied as an attachment to Reference (2).

COMPANION SPECIMEN TEST

The method for obtaining a cyclic stress-strain curve that is most generally accepted, and provides the most technically exact definition, is to define the curve by connecting the tips of stable stress-strain hysteresis loops. These hysteresis loops are obtained by subjecting several like, or companion, material specimens to a defined pattern of alternating tension and compression loading cycles. Each specimen is cycled at a different constant strain amplitude through a series of full strain reversals until plots of their hysteresis loops remain unchanged (i.e., a stabilized hysteresis loop). Figure 1 gives an illustration of the type of constant strain amplitude a specimen was subjected to under the conditions of the Companion Specimen Test. Reference (2) suggests that the number of cycles specified for the test be approximately equal to half the fatigue life of the material such that a fully stabilized condition is reached.

The testing effort to fully define the cyclic stress-strain curve using the companion specimen method could be prohibitive due to the large number of cycles required for each test and the large number of companion specimen data points necessary to generate a well-defined cyclic stress-strain curve. For this reason, a test procedure that could generate a cyclic stress-strain curve from a single test specimen (Incremental Step Test), similar to a monotonic material test, was used to define sets of cyclic data points from which a stress-strain curve could be developed. Data points generated from the Companion Specimen Test were used to verify the resulting cyclic stress-strain curve.

TEST PROCEDURE AND RESULTS

ENGINEERING STRESS AND STRAIN

All test data was recorded and reported as engineering stress and strain. Engineering stress and strain differ from true stress and strain in the following manner. The engineering measure is based on the original specimen diameter. The true measure is based on an updated area calculated from the measured diameter at each instant of loading.

Test control, achieved by monitoring axial strain levels, was accomplished by taking the diametral strain and converting it to axial strain. For the Incremental Step Test, this conversion was performed directly by the MTS 448.38 analog strain computer at the testing laboratory. In addition to diametral strain, measured force was also used as input to the conversion. The pre-test measured specimen diameter was used as the original diameter for strain calculations for each block of testing.

For the Companion Specimen Test, the following algorithm, derived from Reference (1), was used to obtain axial strain for test control;

$$\varepsilon_t = \frac{\varepsilon_d}{\gamma_p} + \frac{\sigma}{E}\left[1 - \frac{\gamma_e}{\gamma_p}\right]$$

where :
- ε_t = total axial strain
- ε_d = diametral strain
- γ_p = plastic Poisson's ratio (0.5)
- γ_e = elastic Poisson's ratio (0.3)
- σ = engineering stress
- E = modulus of elasticity

POISSON'S RATIO CONFIRMATION

Biaxial strain gages were placed on either side (180^{o} apart) of the large diameter region (grip region) of one longitudinal and one transverse specimen. Poisson's ratio was determined with loading in the elastic range of the material.

INCREMENTAL STEP TEST

Sixteen specimens were tested in strain control, at room temperature, on an MTS 20 KIP closed loop servo-hydraulic test machine. The strain wave form consisted of a series of blocks of incrementally decreasing alternating strain with a short (approximately 2 seconds) "hold" at zero strain between blocks. Each block consisted of fifteen (15) cycles of full strain reversals beginning with the designated maximum (+) strain amplitude. Four different maximum strain amplitude conditions were used; 0.5%, 1.0%, 2.5% and 4.0%.

Two specimens from each material orientation (longitudinal and transverse) with respect to plate stock principal rolling direction were tested at each strain amplitude condition. All incremental testing was performed at a strain rate of 0.1% strain per second. For all blocks, the initial load was in the tensile direction. Testing of each specimen continued until stabilization of stress levels occurred between successive blocks. Stabilization was judged to occur by observing the stress versus time plot for each specimen as testing progressed. The specimens were judged to have reached a stabilized condition when indiscernible changes (less than 2.0%) in stress patterns occurred over a significant number of blocks of data.

In several higher strain amplitude tests, testing continued to specimen failure. This occurred from fatigue crack initiation in the gage portion of the test specimen. As crack size increased, the force range decreased. When this change became substantial, testing was terminated to prevent damage to the diametral extensometer.

COMPANION SPECIMEN TEST

The companion specimen test was a low cycle fatigue test. Seventeen specimens were tested in strain control, at room temperature, on the MTS Test Star #2 closed loop servo-hydraulic test machine. Cyclic frequency was based on a strain rate of 0.5% strain per second for all specimens except for specimens L1 and T9. They were tested at a strain rate of 0.1% strain per second. Testing was performed with a 0% mean strain and at the same strain amplitudes as the maximum amplitude for the Incremental Step Tests (0.5%, 1.0%, 2.5% and 4.0%). The first quarter cycle of loading was in the tension (+) direction. A minimum of two specimens from each orientation (longitudinal and transverse) were tested at each of the strain amplitudes. Stabilization criteria was the same as that used for the Incremental Step Tests.

INSTRUMENTATION

MTS diametral extensometers were used to measure change in diameter during all testing. For the Incremental Step Test, a Model No. 632.41B-04 was used with the 906.57 data acquisition system on the MTS 20 KIP test machine that was equipped with 448 electronics and a Nicolet storage oscilloscope. For the Companion Specimen Test, a Model No. 632.20B-20 with the 315.81B data acquisition system was used on the MTS Test Star #2 test machine.

DATA ACQUISITION

Data acquisition for the Incremental Step Test included real time stress versus strain plots of selected blocks and stress/strain versus time for the test duration. The maximum and minimum stress and strain values at each reversal point were printed to hard copy and subsequently used to generate the cyclic stress-strain curves for the initial block and the stabilized block for each specimen. Stress, strain and time data points defining the hysteresis loops of selected blocks were captured on a storage oscilloscope and transferred to magnetic media.

Data acquisition for the Companion Specimen Test was per Reference (1). This included specimen and test parameters, and maximum and minimum values of stress and strain during the test and hysteresis plots of selected cycles. Three hundred data points per cycle for the values of strain, force and time were stored on magnetic media.

The diametral extensometer used for test control measured a change in specimen diameter in a single plane. There was concern that test results may have been influenced by the direction this measurement was being taken with respect to the principal rolling direction of the plate. Therefore, one of the two specimens for each orientation and strain amplitude was tested with the diametral measurement in the same plane as the principal rolling direction and the second specimen measurement was taken at 90 degrees from the first.

TEST RESULTS

The Incremental Step Test data at the four maximum strain values are summarized in Table 1. The 0.2% offset yield stress value is listed for the monotonic and cyclic stress-strain curves. The monotonic values represent the initial specimen loading that corresponds to the yield stress value normally reported from a static stress-strain test. Stabilization was judged to occur at the block of data where no appreciable change was observed in the hysteresis behavior from that of the previous block. The yield stress value from the cyclic stress-strain curve is the offset value calculated from the cyclic curve obtained by connecting the tips of the hysteresis loops of the stabilized load block.

The cyclic stress-strain curve, compiled from all test data, is included as Figure 2. The cyclic behavior observed in the Incremental Step Test can be illustrated by considering Figures 3 through 6. Figure 3(a) shows a plot of the superimposed hysteresis loops for Block 1 of specimen L9, that was cyclically loaded to a maximum strain value of 0.5%. In this plot, the initial strain cycle, from which the monotonic value is taken, is evident as the curve that attains the maximum, positive value. Figure 3(b) is the superimposed hysteresis plot for the stabilized condition, Block 118, of the same specimen. The curves are fairly symmetric about the axes and material softening is evident by comparing the maximum stress values attained for the two blocks (-89.13 KSI for Block 1 vs. -74.77 KSI for Block 118).

The other plots included for the Incremental Step Test were those from specimen L7. This specimen was subjected to a maximum strain value 4.0%. Cyclic stress-strain curves from the initial and stabilized blocks for specimen L7 are included as Figures 4a and 4b respectively.

Comparisons of the initial versus the stabilized block cyclic stress-strain curves for specimens L7 and L9 are shown in Figures 5 and 6, respectively. Cyclic softening of the material is demonstrated by the difference between the initial and stabilized cyclic stress-strain curves. The softening behavior appears more pronounced for the L9 specimen which was subjected to a lower value of maximum strain (0.5%). This specimen requires a large number of cycles to reach a stabilized state. The L7 specimen which was subjected to a higher level of strain (4.0%) requires fewer cycles to reach stabilization and failure. The amount of cyclic softening that occurs appears to be proportional to the number of strain cycles required for stabilization which, in turn, is a function of the maximum strain amplitude. The lower number of load blocks required to reach stabilization and failure for the higher strain levels is not sufficient to develop the dramatic cyclic softening behavior observed for the lower strained specimens, however, softening does occur since the data points for the stabilized curve are slightly lower in magnitude than the initial curve. Therefore, the higher the maximum strain amplitude for the initial cycle of the loading block, the less pronounced the softening response.

For the L7 specimen which was tested at the higher strain level (4.0%) stress at the maximum tensile strain is not the maximum stress value for the loading block (Figure 6). The initial cycle of each load block subjects the specimen to the maximum tensile strain for that test. The strain amplitude of subsequent cycles decreases linearly to zero. Due to the higher levels of inelastic straining, a small amount of additional strain hardening occurs during the initial cycle of each load block. This additional strain hardening causes the stress level of the second tensile peak to be higher than the first, even for a slightly lower strain level. This hardening phenomenon appears to mitigate for subsequent cycles and stress levels continuously decrease along with strain levels. This effect is not seen for compressive strain since the majority of the hardening occurs during initial tensile loading.

The Companion Specimen Test data is summarized in Table 2. The cyclic behavior observed in the Companion Specimen Test can be illustrated by considering Figures 7 and 8. Stress at both the maximum tensile and compressive strain values during the loading history of each specimen is listed for the stabilized loop (cycle). As can be seen, stabilization occurred at a different number of loading cycles, depending on the strain amplitude, for each test specimen. The cycles to specimen failure also reflect the dependence on the strain amplitude. Stabilization and failure of the specimen occurred at significantly fewer cycles in those specimens subjected to the higher strain amplitudes (2.5% and 4.0%). Failure was judged to occur at the loading cycle where the specimen experienced a 90% or greater decrease in peak tensile stress, when compared to a stabilized, steady state cycle.

Each Companion Specimen Test yields two data points for the maximum tensile and compressive stress values at the maximum strain amplitude for each test specimen at stabilization. A hysteresis plot for the initial (Block 1) and stabilized (Block 5000) cycle of loading for Specimen L6 is included in Figure 7. This specimen was subjected to a constant strain amplitude of +/-0.5%. As in the previous test method, a similar monotonic curve results from the initial load cycle. Unlike the previous test, the strain magnitude remains constant for as many cycles as required until failure. Data points for the cyclic stress-strain curve are determined by the stress values located at the tips of the hysteresis loop for the stabilized condition.

As in the Incremental Step Test, the 0.5% and 1.0% specimens from this test showed significant softening when comparing the initial load cycle to a stabilized cycle (0.5% specimen shown in Figure 7). For the specimens tested at the higher strain amplitudes (2.5% and 4.0%), softening is less pronounced (4.0% specimen shown in Figure 8).

CONCLUSIONS

The cyclic stress-strain curve is determined by connecting the tips of the stabilized block hysteresis loops for the Incremental Step Test specimens.

The results of this test program show that the maximum tensile and compressive stress-strain coordinates of the stable Companion Specimen Test hysteresis loops are reasonably coincident with the cyclic stress-strain curve data derived from the Incremental Step Test.

Stress and strain response from the first several cycles of the Companion Specimen Test and the first block of loading from the Incremental Step Test provide insight into the initial cycle hardening/softening characteristics of high yield strength steel when subjected to inelastic strain histories typical of rapidly applied transient dynamic type loads. In addition, this data, obtained using very controlled and repeatable testing methods, can be used as a uniaxial verification of material model enhancements made in the finite element codes used to perform nonlinear elastic-plastic analysis.

The cyclic test results show a high degree of consistency and repeatability. There appears to be no significant effect on test results due to specimen strain measurement direction with respect to material rolling direction or strain rate. Test results indicate no significant differences between transverse and longitudinal specimens for similar test conditions. Additionally, Incremental Step Test specimens loaded to different maximum strain amplitudes produce reasonably coincident cyclic stress-strain curves up to their respective strain limits.

The general trend of high yield strength steel plate material is to cyclically soften. This behavior is apparent in the cyclic test results when comparing hysteresis data for the initial, intermediate, and stabilized blocks of data from the Incremental Step Test. It is also confirmed in the Companion Specimen Test plots of stress versus number of cycles where stress values decrease as the specimen reaches a state of stabilized stress. The higher strain tests show some work hardening after an initial softening period. This is shown by the increased maximum/minimum stress values for some specimens after stabilization has been attained. The plots of stress versus number of cycles for the Companion Specimen Test may also suggest this behavior with a slight upturn in maximum stress just prior to failure for some specimens.

To accurately model elastic-plastic behavior of initially unstrained structures, including inelastic strain reversals, the initial plastic behavior typified by the monotonic stress-strain curve should be included in the material model as well as a method to account for the difference in the cyclic strain history of the first several inelastic strain reversals. The results from this test program can be used to develop and verify such a material model for use in elastic-plastic finite element analysis.

REFERENCES

(1) ASTM E606-92, Standard Practice for Strain-Controlled Fatigue Testing, Annual Book of ASTM Standards, Volume 03.01, 1995 edition

(2) "Determination of the Cyclic Stress-Strain Curve," Journal of Materials, JMLSA, Landgraf, R. W., Morrow, J., and Endo, T., Vol. 4, No. 1, March 1969, pp. 176-188

SPEC. ID	MAXIMUM STRAIN AMPLITUDE (%)	0.2% YIELD STRESS (KSI) MONOTONIC STRESS-STRAIN CURVE	STABILIZED BLOCK NO.	CYCLIC STRESS-STRAIN CURVE	CYCLIC BEHAVIOR
L8	0.5	88.51	130	67.41	S
L9	0.5	88.98	118	68.52	S
T4	0.5	89.20	108	68.89	S
T8	0.5	88.72	109	68.89	S
L2	1.0	87.54	91	64.44	S
L11	1.0	87.93	60	65.19	S
T10	1.0	88.51	60	65.19	S
T12	1.0	88.47	51	66.36	S
L3	2.5	87.39	32	68.89	S-H
L4	2.5	87.20	45	69.78	S
T3	2.5	89.04	24	67.78	S
T5	2.5	88.43	25	68.44	S-H
L6	4.0	87.19	11	72.89	S-H
L7	4.0	86.86	8	72.44	S-H
T7	4.0	89.11	10	72.00	S-H
T12A	4.0	88.16	14	71.56	S-H

KEY
S - MATERIAL CYCLICALLY SOFTENS
S-H - MATERIAL CYCLICALLY SOFTENS THEN HARDENS

<u>Table 1</u> Incremental Step Test

SPEC. ID	STRAIN AMPLITUDE (%)	STABILIZED HYSTERESIS LOOP LOOP NO.	STRESS AT MAX STRAIN (KSI)	STRESS AT MIN STRAIN (KSI)	CYCLES TO FAILURE
L6	0.5	5000	67.5	-68.9	8036
T9	0.5	5000	68.4	-70.7	7640
L1	0.5	5000	68.1	-70.3	7586
T(2)8	0.5	4000	68.1	-70.0	6267
L5	1.0	500	77.7	-80.0	1322
T(2)14	1.0	600	79.0	-81.1	1613
L3	1.0	800	78.6	-81.7	1496
T(2)16	1.0	500	78.7	-82.1	981
T(2)6	1.0	500	77.4	-79.9	1055
L(2)5	2.5	90	89.9	-95.5	175
T(2)13	2.5	90	89.6	-95.6	173
L(2)2	2.5	90	90.9	-97.1	172
T(2)17	2.5	110	90.7	-95.8	213
L(2)7	4.0	28	96.0	-105.2	56
T(2)4	4.0	40	98.5	-107.2	84
L(2)3	4.0	40	100.1	-110.4	82
T(2)9	4.0	50	98.7	-108.8	81

STRAIN AMPLITUDE (%)	STRAIN RATE (% / SEC)	FREQUENCY (HZ)	
0.5	0.5	0.250	L6 & T(2)8
0.5	0.1	0.050	T9 & L1
1.0	0.5	0.125	
2.5	0.5	0.050	
4.0	0.5	0.031	

CYCLES TO FAILURE - CYCLE IN WHICH 90% OR GREATER DECREASE IN PEAK TENSILE STRESS, FROM A STEADY STATE CYCLE IS DETECTED.

<u>Table 2</u> Companion Specimen Test

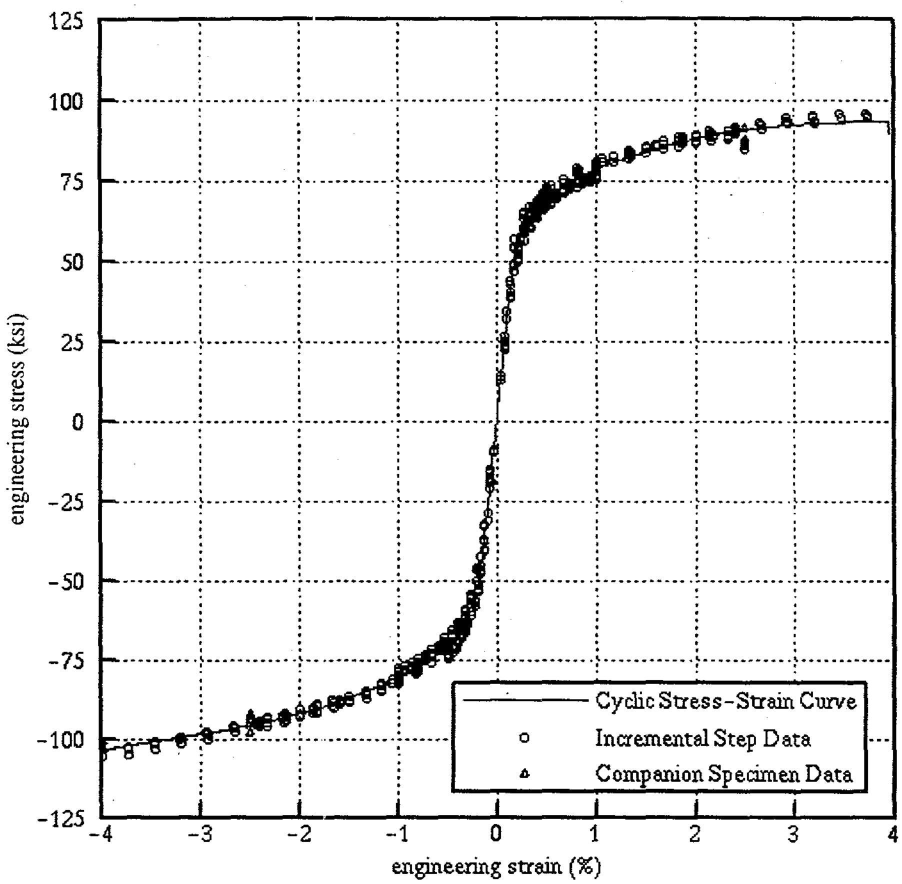

Figure 2. Composite Cyclic Engineering Stress-Engineering Strain Curve "Fitted" to Cyclic Test Data

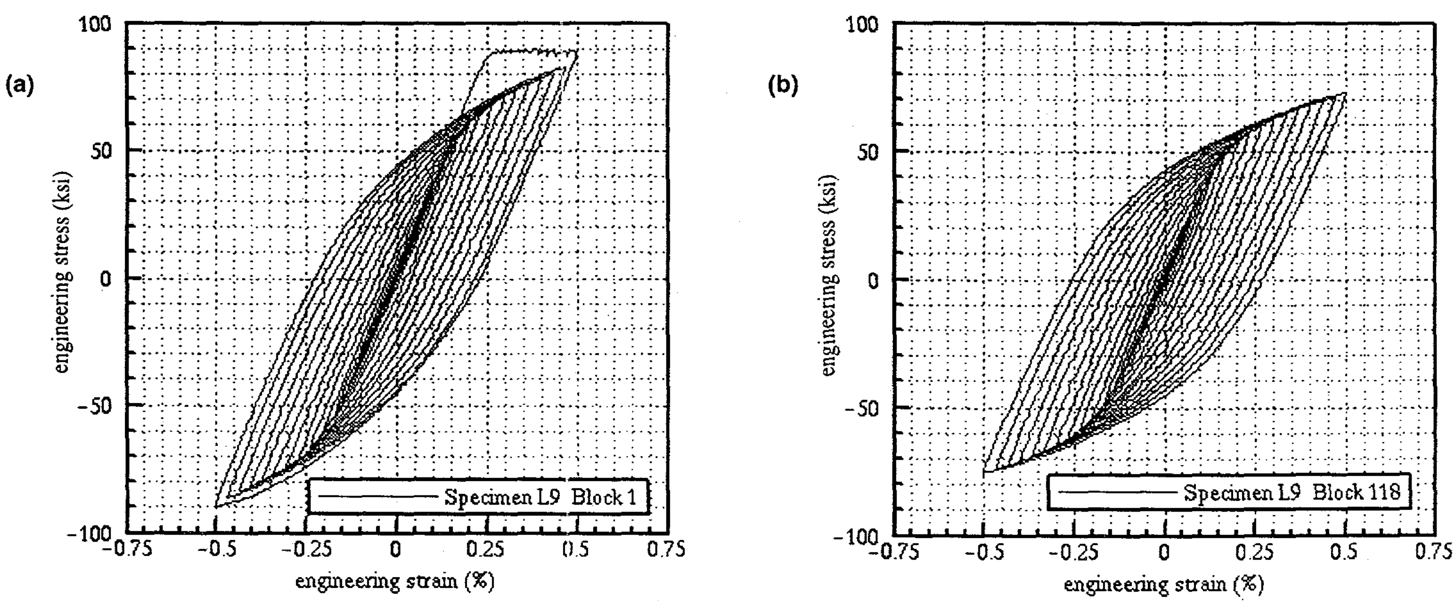

Figure 3. Cyclic Stress-Strain Hysteresis Loops for Incremental Test Specimen L9 from the (a) Initial Load Block and (b) Stabilized Load Block

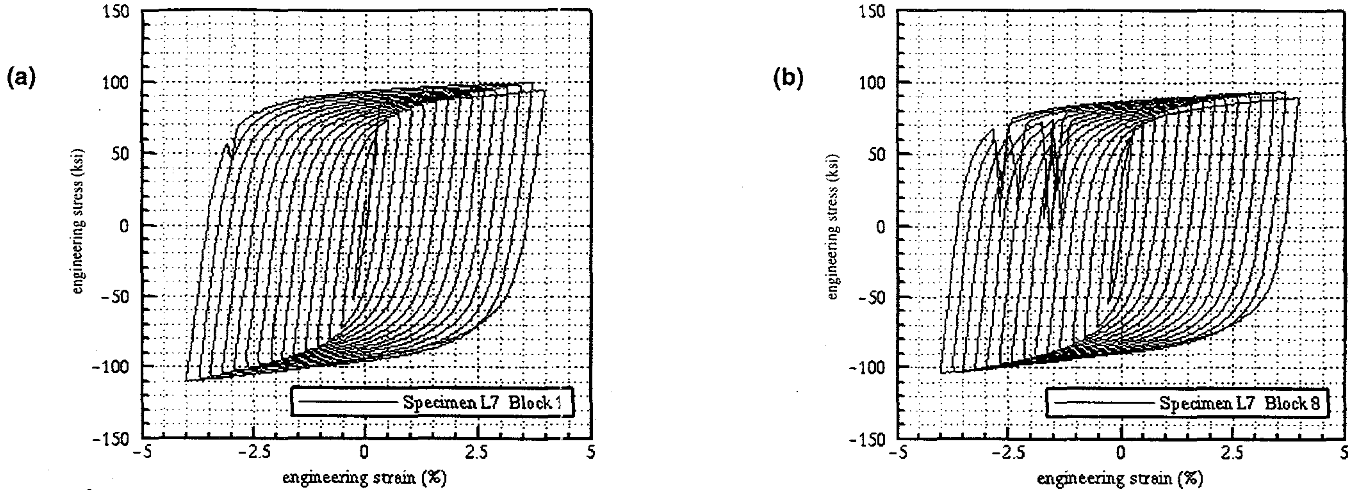

Figure 4. Cyclic Stress-Strain Hysteresis Loops for Incremental Test Specimen L7 from the (a) Initial Load Block and (b) Stabilized Load Block

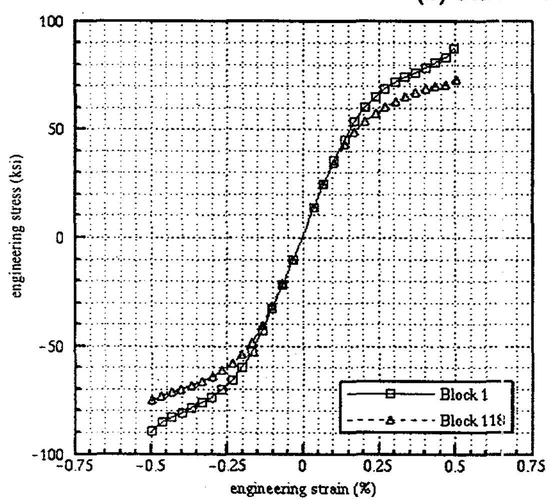

Figure 5. Specimen L9 Cyclic Stress-Strain Curves from Initial and Stabilized Load Blocks

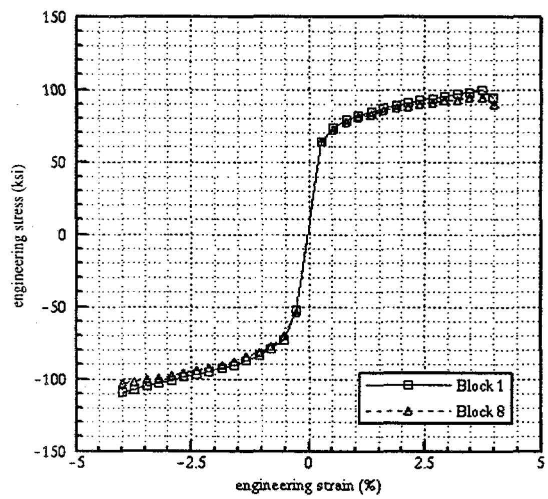

Figure 6. Specimen L7 Cyclic Stress-Strain Curves from Initial and Stabilized Load Blocks

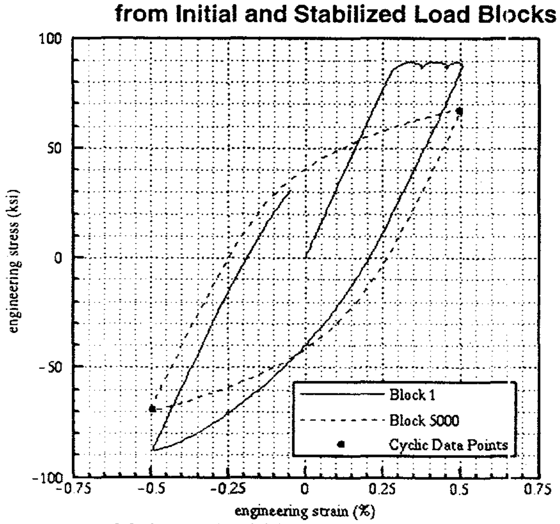

Figure 7. Initial and Stabilized Stress-Strain Hysteresis Loops for Companion Test Specimen L6

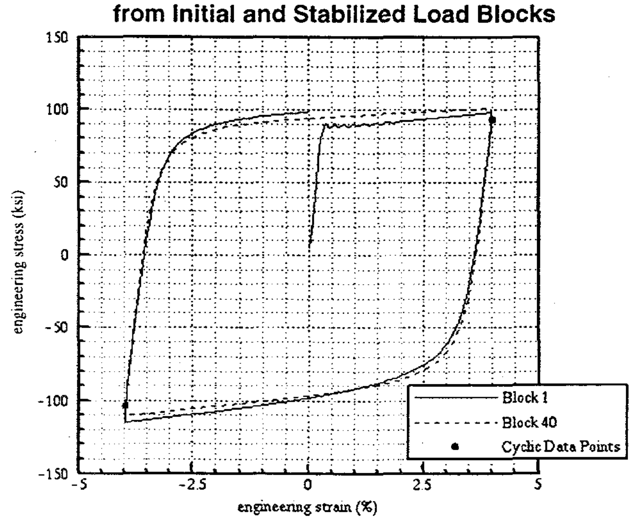

Figure 8. Initial and Stabilized Stress-Strain Hysteresis Loops for Companion Test Specimen L(2)3