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NOTICE

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Peter Dusicka[1], Ahmad M. Itani[2] and Ian G. Buckle[3]

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1 Assistant Professor, Department of Civil and Environmental Engineering, Portland State University; former Graduate Student, Department of Civil Engineering, University of Nevada-Reno
2 Associate Professor, Department of Civil Engineering, University of Nevada-Reno
3 Professor and Director of Center for Civil Engineering Earthquake Research, Department of Civil Engineering, University of Nevada-Reno

MCEER
University at Buffalo, The State University of New York
Red Jacket Quadrangle, Buffalo, NY 14261
Phone: (716) 645-3391; Fax (716) 645-3399
E-mail: *mceer@buffalo.edu*; WWW Site: *http://mceer.buffalo.edu*

Preface

The Multidisciplinary Center for Earthquake Engineering Research (MCEER) is a national center of excellence in advanced technology applications that is dedicated to the reduction of earthquake losses nationwide. Headquartered at the University at Buffalo, State University of New York, the Center was originally established by the National Science Foundation in 1986, as the National Center for Earthquake Engineering Research (NCEER).

Comprising a consortium of researchers from numerous disciplines and institutions throughout the United States, the Center's mission is to reduce earthquake losses through research and the application of advanced technologies that improve engineering, pre-earthquake planning and post-earthquake recovery strategies. Toward this end, the Center coordinates a nationwide program of multidisciplinary team research, education and outreach activities.

MCEER's research is conducted under the sponsorship of two major federal agencies, the National Science Foundation (NSF) and the Federal Highway Administration (FHWA), and the State of New York. Significant support is also derived from the Federal Emergency Management Agency (FEMA), other state governments, academic institutions, foreign governments and private industry.

The Center's Highway Project develops improved seismic design, evaluation, and retrofit methodologies and strategies for new and existing bridges and other highway structures, and for assessing the seismic performance of highway systems. The FHWA has sponsored three major contracts with MCEER under the Highway Project, two of which were initiated in 1992 and the third in 1998.

Of the two 1992 studies, one performed a series of tasks intended to improve seismic design practices for new highway bridges, tunnels, and retaining structures (MCEER Project 112). The other study focused on methodologies and approaches for assessing and improving the seismic performance of existing "typical" highway bridges and other highway system components including tunnels, retaining structures, slopes, culverts, and pavements (MCEER Project 106). These studies were conducted to:

- assess the seismic vulnerability of highway systems, structures, and components;
- develop concepts for retrofitting vulnerable highway structures and components;
- develop improved design and analysis methodologies for bridges, tunnels, and retaining structures, which include consideration of soil-structure interaction mechanisms and their influence on structural response; and
- develop, update, and recommend improved seismic design and performance criteria for new highway systems and structures.

The 1998 study, "Seismic Vulnerability of the Highway System" (FHWA Contract DTFH61-98-C-00094; known as MCEER Project 094), was initiated with the objective of performing studies to improve the seismic performance of bridge types not covered under Projects 106 or 112, and to provide extensions to system performance assessments for highway systems. Specific subjects covered under Project 094 include:

- development of formal loss estimation technologies and methodologies for highway systems;
- analysis, design, detailing, and retrofitting technologies for special bridges, including those with flexible superstructures (e.g., trusses), those supported by steel tower substructures, and cable-supported bridges (e.g., suspension and cable-stayed bridges);
- seismic response modification device technologies (e.g., hysteretic dampers, isolation bearings); and
- soil behavior, foundation behavior, and ground motion studies for large bridges.

In addition, Project 094 includes a series of special studies, addressing topics that range from non-destructive assessment of retrofitted bridge components to supporting studies intended to assist in educating the bridge engineering profession on the implementation of new seismic design and retrofitting strategies.

Due to the lack of experimental data on the stress-strain behavior of specialty steels and conventional grade steels, a comprehensive study on the stress-strain and low cycle fatigue properties was conducted. The purpose of the study was to evaluate the stress-strain characteristics of plate steels subjected to repeated cyclic plastic deformations. The steel grades ranged from high performance steel HPS 485MPa to low yield point steel LYP Grade 100 MPa. Of specific interest was the cyclic stress as measured relative to the yield strength and the variability of the achieved stresses across the different steel grades. In addition, low cycle fatigue characteristics were desired to compare the fatigue life. The experimental results showed that all of the steels would be suitable for earthquake engineering applications, although the effects of welding or multi-axial stresses were not considered.

ABSTRACT

An experimental evaluation of the stress-strain behavior and the low cycle fatigue life was conducted on five grades of plate steel to determine their suitability for use in earthquake structural engineering applications. The steel grades ranged from high performance steel HPS 485 MPa (70 ksi) to low yield point steel LYP Grade 100 MPa (14.5 ksi). The coupons were tested to failure using complete reverse cyclic axial strains of primarily constant strain amplitude between 1% and 7% strain and at constant strain rate of 0.1%/*sec*. The cyclic stress increased with strain amplitude for all of the steels, but the experimental results also indicated a strong dependency on the steel grade. The cyclic stress-strain response was idealized by a power law relationship and cyclic hardening was evident in specific cases when compared to the monotonic response. The cyclic stress was nearly 2 times the yield stress for A709 Grade 345 MPa (50 ksi) and nearly 5 times the yield stress for low yield point steels LYP Grade 100 MPa (14.5 ksi). In all cases the majority of the cyclic hardening occurred within the first several reversals. From the limited number of dynamic test results, the dynamic strain rate had negligible effect on the yield strength, cyclic stress-strain response as well as the fatigue life. The low cycle fatigue life of the different steels did vary, but overall the fatigue life was relatively similar for all grades. The experiments showed that all of the steels would be suitable for earthquake engineering applications, although the effects of welding or multi-axial stresses were not considered.

ACKNOWLEDGEMENTS

High performance steel was provided by Oregon Steel Mills (Portland, OR) and low yield point steel shear links by Nippon Steel (Japan). The generous assistance of Dr. Ian Aiken and Dr. Isao Kimura is also gratefully acknowledged.

The successful completion of the laboratory experiments would not be possible without the hard work of Dr. Patrick Laplace and the helpful assistance of Paul Lucas.

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IMPORTANCE OF INELASTIC CYCLIC STEEL BEHAVIOR

1.1 Earthquake Loading and Low Cycle Fatigue

Failure in metal structures caused by fatigue is mainly attributed to the accumulation of large numbers of cycles of low amplitude strain, which is nominally considered within the elastic range for the gross section. This form of fatigue is classified as high cycle fatigue and continues to be an important consideration to mechanical and structural engineers alike. Design provisions have been formulated to account for high cycle fatigue throughout the life of structures susceptible to these types of failures, mainly bridges (AASHTO 1998). However, an additional important classification of fatigue that is important to structural engineers is that of low cycle fatigue.

Low cycle fatigue is characterized by large plastic strains leading to material failure that occurs within a low number of cycles. These conditions can develop in specific parts of a structure when subject to rare but extreme loading, such as that generated by an earthquake. Plastic deformation is inherent in the seismic design philosophy, because structural damage without collapse is acceptable (UBC 1997, AISC 2002). Better understanding of material low cycle fatigue behavior is therefore important for determining the suitability of a material and eventual prediction of service life of structural components subject to large strain demands. Numerical models with appropriate stress-strain and fatigue life properties can be developed for implementation in computer models to further study the structural component behavior under these demanding situations.

1.2 Objectives

Due to the lack of experimental data on the stress-strain behavior of not only the specialty steels but also the conventional grade steels, a comprehensive study on the stress-strain and low cycle fatigue properties was conducted. The purpose of the study was to evaluate the stress-strain characteristics of plate steels subjected to repeated cyclic plastic deformations. Of specific interest was the cyclic stress as measured relative to the yield strength and the variability of the achieved stresses across the different steel grades. In addition, low cycle fatigue characteristics were desired to compare the fatigue life.

1.3 Overview of Low Cycle Fatigue Steel Research

Despite the necessity of understanding steel low cycle fatigue behavior as it relates to earthquake engineering, limited literature addresses the issue of the material low cycle fatigue specifically. Most earthquake related research has not evaluated the structural steel material itself, but instead concentrated on the behavior of structural components or entire assemblies under cyclic loading. Bertero and Popov (1965) were one of the first researchers to investigate the effect of plastic strains on beam deformation behavior. The main objective of their study was to investigate premature buckling of flanges, but strains were also monitored and recorded to be up to 2.5%. Since then, most research has focused on structural component behavior with a large number of experiments on beam column joints. Recently, this type of research concentrated primarily on welded steel moment frame joints after the observed damage following the Northridge Earthquake in 1994 (Malley 1998). Bending tests were also conducted on machined cone shaped steel cantilever studs intended to be used as structural earthquake energy dissipators (Buckle & King 1988). The recorded strains reached up to 10%, however similar to the beam-column experiments these maximum strains were only located in the outer fibres of the components due to the bending action.

To effectively investigate material characteristics, the cross section should be under uniform strain distribution as in the case of axial loading. Limited information regarding steel low cycle fatigue behavior is available from overseas research. New Zealand reinforcing steel, which was produced based on New Zealand Standard NZS 6402-1989 in Grade 300 *MPa* and 430 *MPa*, was investigated for plastic stress strain behavior using coupons machined from rebar (Dodd, 1992). Unfortunately, the cycles were not fully reversed as the compression deformations were not equally attained when compared to the tension deformations due to test setup limitations and specimen buckling issues. Japanese researchers conducted low cycle fatigue coupon experiments on low yield point steels for potential use as energy dissipation mechanism in base isolation or for unbonded braces (Eiichiro et. al., 1998). The study considered 44 coupons tested with constant strain amplitudes ranging from 0.15% to 1.5%, but only included two specimens at 1.5% strain with the remainder all under 1% amplitude strain. The strain in structural components that are inelastically resisting earthquake loads can be significantly higher.

Most importantly, no low cycle fatigue data was available for plate steels that are typically used for steel bridge fabrication in the United States. The most relevant data was obtained from a study investigating the mechanical properties of inelastically pre-strained A572 steel in order to assess the manufacturing strengthening procedures on the ductility of the k-region of rolled wide flange beams (Kaufmann et al 2001). As part of this study, axial coupon tests were conducted at strain amplitudes of 1%, 3% and 4% strain on four grades of steel, two made from ASTM A572 and one of each of A992 and A36. Only three coupons in total of A572 steel were taken to their fatigue life. The remainder was tested to only 10 cycles, but the test results did provide experimental data on cyclic plastic stress-strain behavior. Experimental data on plate steels or the recently introduced high performance steels was not available.

1.4 Review of Analytical Models for Cyclic Behavior

Several analytical relationships have been proposed for modeling the mechanical behavior of steel materials for the purpose of structural analyses. These models include non-linear stress-strain as well as fatigue life relationships.

1.4.1 Nominal and True Stress and Strain

The nominal stress σ_{nom} and the average nominal strain ε_{nom} are typically calculated directly from experimental measurements. The nominal values can be related to the true stress σ and strain ε using Equation 1-1 and Equation 1-2. Plastic strain was separated from the total strain using Equation 1-3.

$$\varepsilon = \ln(1 + \varepsilon_{nom}) \tag{1-1}$$

$$\sigma = \sigma_{nom}(1 + \varepsilon_{nom}) \tag{1-2}$$

$$\varepsilon_p = \varepsilon - \varepsilon_e = \varepsilon - \frac{\sigma}{E} \tag{1-3}$$

Diametric strain occurs due to the change in cross sectional area from the applied axial load. The diameter increases for compressive axial strains and decreases for tensile axial strains. The diametric strain ε_d of the coupon was calculated using Equation 1-4, which consists of an elastic term involving the poisson ratio μ

and the plastic term that assumes constant volume. The diametric strain can be incorporated as part of a stress modification factor to the original stress σ_o for each data point using Equation 1-5 (Jiang 2004).

$$\varepsilon_d = \mu \cdot \frac{\sigma}{E} + 0.5(\varepsilon - \varepsilon_p) \tag{1-4}$$

$$\sigma = \sigma_o \cdot \frac{1}{(1 - \varepsilon_d)^2} \tag{1-5}$$

1.4.2 Stress-Strain Bi-linear Relationship

The basic estimation of stress-strain relationships in structural analysis and design consist of two linear segments. The elasto-plastic relationship models a linear elastic stiffness and assumes no post-yield stiffness. The effects of strain hardening can be incorporated by introducing a constant linear slope for the post-yield stiffness, forming a bi-linear relationship. The post yield slope can vary depending on the steel material from 0.005 to 0.05 times the elastic stiffness and can be obtained for example by equating the area under the stress-strain curve from a simple tension coupon test. (Bruneau et al, 1998) These models are crude approximations for describing material stress-strain behavior and their usefulness is therefore limited.

1.4.3 Stress-Strain Power Function Relationship

A power function can be used to more closely approximate the stress-strain behavior of cyclically loaded metals (Bannantine et. al. 1990). A log-log plot of true stress versus true plastic strain has generally been approximated by a straight line resulting in the power law function expressed in Equation 1-6 as the basis for the cyclic stress-strain curve.

$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K}\right)^{1/n} \tag{1-6}$$

where ε = true strain
σ = true stress
E = elastic modulus
K = cyclic strain coefficient
n = cyclic strain hardening exponent

The strain hardening coefficient and exponent can be obtained from regression of experimental stress versus plastic strain data using a power equation. For a complete hysteresis loop, the stress and strain values can be doubled based on Massing's hypothesis (Massing 1926) to obtain equations using strain range $\Delta\varepsilon$ and stress range $\Delta\sigma$. The resulting Equation 1-7 becomes applicable for any arbitrary start point and describes the stress-strain relationship over the strain range.

$$\Delta\varepsilon = \frac{\Delta\sigma}{E} + 2\left(\frac{\Delta\sigma}{2K}\right)^{1/n} \tag{1-7}$$

1.4.4 Fatigue Strain-Life Relationship

The approach most often used in estimating fatigue life in structural design is the stress-life approach. The stress-life approach relates the alternating stress to the number of cycles to failure and is often used for design over the service life of the structure for high-cycle fatigue. Since this method does not specifically account for plastic behavior, it is unsuitable for low cycle fatigue applications. The observation that in many components the fatigue response of the material is deformation dependant led to the development of the strain-life approach of modeling fatigue behavior. The Coffin-Manson law (Manson 1953, Coffin 1954) relates the plastic strain amplitude to the number of reversals to failure and when combined with an elastic term, the relationship in Equation 1-8 results.

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f'}{E}(2N_f)^b + \varepsilon_f'(2N_f)^c \tag{1-8}$$

where

$(\Delta\varepsilon/2)$ = strain amplitude
$2N_f$ = reversals to failure (1 reversal = 0.5 cycles)
σ_f' = fatigue strength coefficient
b = fatigue strength exponent
ε_f' = fatigue ductility coefficient
c = fatigue ductility exponent

The plastic term of the equation dominates low cycle fatigue behavior as shown in the strain life curve representation in Figure 1-1. The coefficients and exponents can be obtained from regression of experimental fatigue data to the individual relationships of elastic and plastic parts of the strain life equation. The range of interest for earthquake applications is in the early stages of low cycle fatigue as structural components can be strained to fracture within just a few reversals.

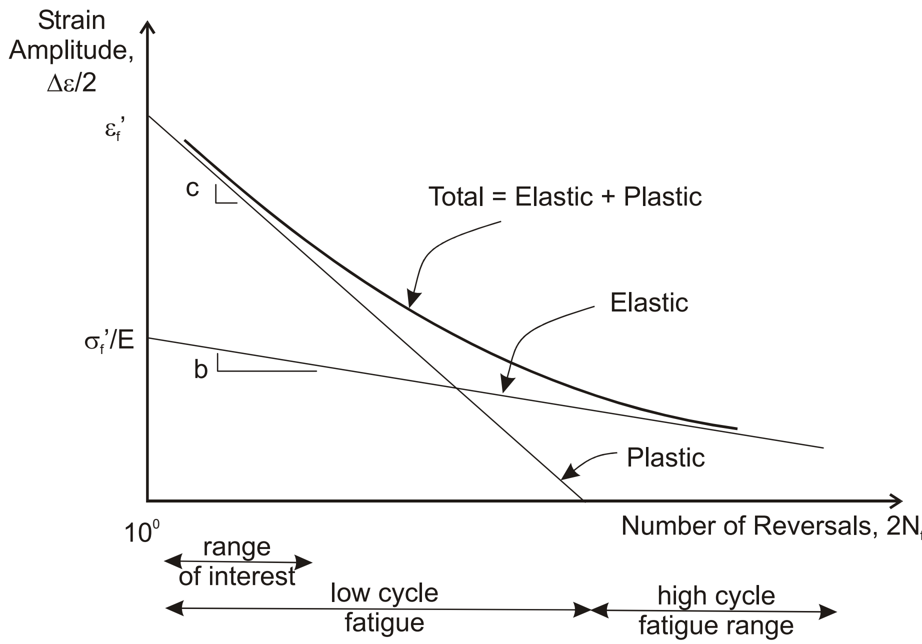


Figure 1-1: Strain-Life Schematic

SECTION 2
TEST SETUP AND LOAD HISTORY

2.1 Equipment and Instrumentation

The stress-strain and low cycle fatigue experiments were conducted on steel coupons subjected to cyclic strains. A MTS fabricated load frame assembly Model 311.31 photographed in Figure 2-1, was used to subject the steel coupon to axial deformations. This self reacting loading apparatus has a load capacity of ±980 *kN* (±220 *kip*) and maximum stroke of ±203 *mm* (±8 *in*). The applied force was measured using a load cell that was bolted to the bottom of the assembly. Hydraulic grips were used to mount the specimen such that both tension as well as compression loads could be applied. A laser extensometer MTS model no. LX500 photographed in Figure 2-2 and capable of measuring to ±0.002 *mm* (±0.0001 *in*) accuracy was utilized for the axial deformation measurements.

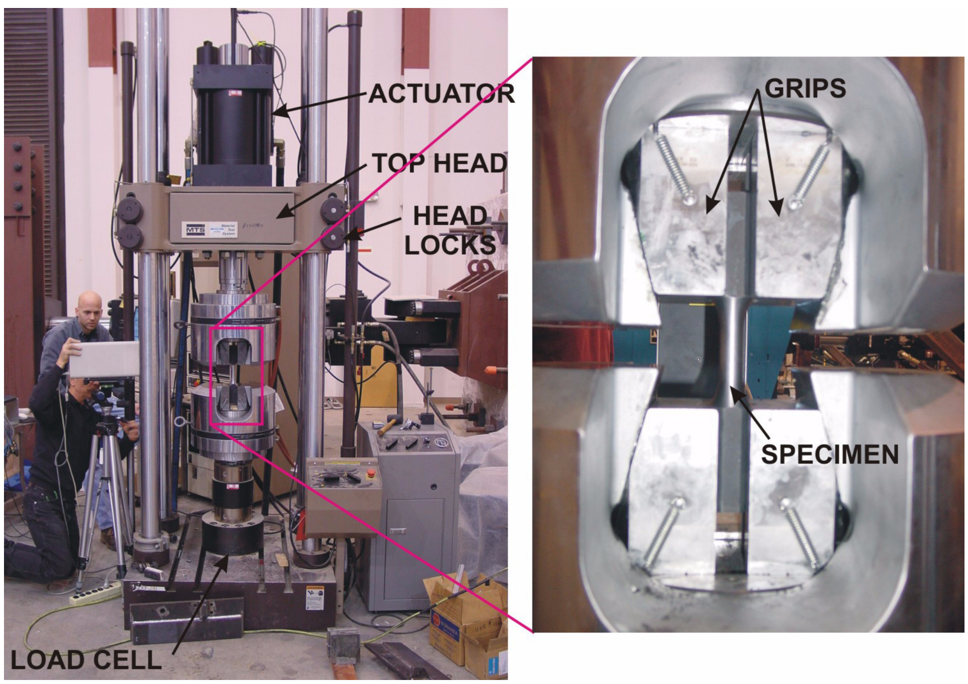


Figure 2-1: Photograph of Load Frame Used for Coupon Tests

2.2 Test Coupon Dimensions and Installation

The test specimens were machined from flat plates into round coupons with reduced section effective length as detailed in Figure 2-3. The reduced section diameter was maintained at 20 *mm* (0.79 *in*) with an effective length of 25 *mm* (0.98 *in*) to minimize buckling. The transition zone was machined using CNC (computer numerical controlled) equipment such that no undercut would result. Typically the surface finish has significant effect on high cycle fatigue results, but is not as crucial for large amplitude low cycle fatigue. For consistency among all of the tests, the surface finish was polished using 440 grit sand paper for all specimens.

Figure 2-2: Photograph of Laser Extensometer Measuring Coupon Deformation

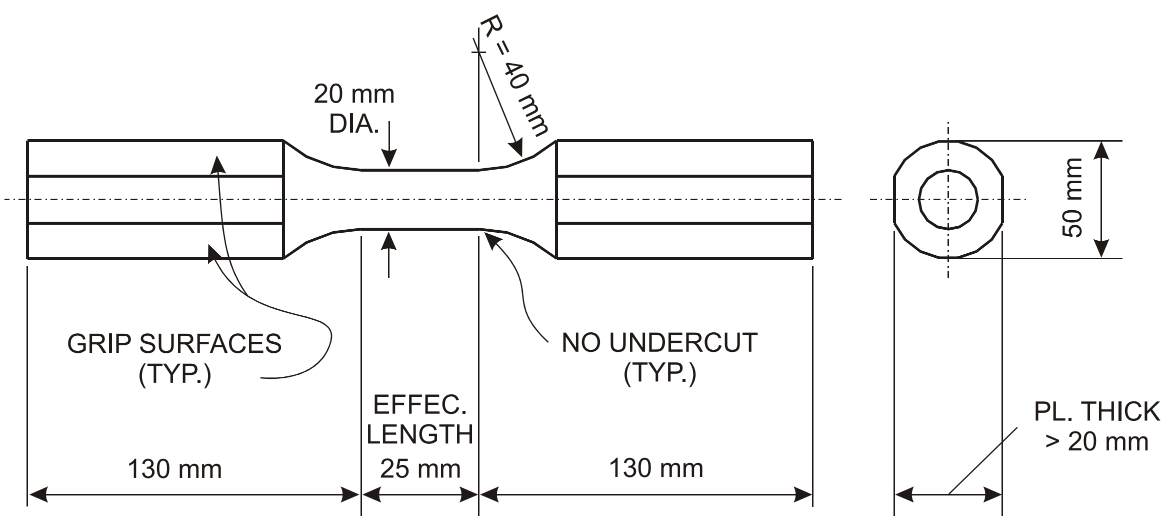


Figure 2-3: Coupon Dimensions

Installation of each specimen required close attention, especially for lower yield steels. The hydraulically driven grips have capacity to induce significant radial forces and can crush the specimen during installation. To avoid this undesired deformation while at the same time providing sufficient resistance against slippage, the grip pressure was maintained between 15-20 *MPa* (2200-2900 *psi*). Similarly, to minimize axial forces during installation, the top head of the load frame pictured in Figure 2-1 needed to remain unlocked until the grips finished engaging the coupon and until the hydraulics were turned to full pressure. Otherwise pressure spikes can prematurely yield the specimen given its high stiffness.

2.3 Steel Material Details

The steels considered for the study consisted of plate steels with steel nominal properties and abbreviations as summarized in Table 2-1.The range in the nominal yield strength provided a wide spectrum of materials that can be grouped into two general categories; structural grade steels and low yield point (LYP) steels. The structural grade steels are typically used for fabrication and construction of entire structures. Their application also extends to specific areas of expected plastic deformations induced by earthquake loading. This category included the high performance steel (HPS) that is gaining acceptance in steel girder bridges (Yost & Funderburk 2001).

In contrast, LYP steels were specifically developed for use in areas of expected inelasticity under earthquake loads and are not likely to be incorporated in the primary gravity load carrying structure. The focus of the study remained on steels that were used for in large-scale experiments of built up shear links (Dusicka et al 2006). HT440 was incorporated in the connection regions and in one link type in the flanges, it was also included in the material study for completeness by being grouped with the structural grade steels.

The material used for the low cycle fatigue tests was obtained from the same original plates that were used for the webs of the shear links except for GR345. The original plate for GR345 was not available and so a plate of the same grade of steel was substituted. The chemical composition summarized from the mill certificates is included in Table 2-2. The mechanical properties were determined using the average values obtained from the coupons tested as part of this study and are summarized in Table 2-3. The yield strength was obtained using the 0.2% offset method.

Table 2-1: Steel Grades Considered

Property	Steel				
	GR345	HPS485	HT440	LYP100	LYP225
General Category	Structural Grade Steels			Low Yield Point (LYP) Steels	
Steel Abbreviation	GR345	HPS485	HT440	LYP100	LYP225
Specification	ASTM A709M Grade 345W	ASTM A709M HPS 485W	BT-HT440C[a]	BT-LP100*	BT-LP225*
Country of Origin	USA	USA	Japan	Japan	Japan
Specified Nominal Yield Strength	345 *MPa* (50 *ksi*)	485 *MPa* (70 *ksi*)	440 *MPa* (64 *ksi*)	100 *MPa* (14.5 *ksi*)	225 *MPa* (32.5 *ksi*)

a Nippon Steel (Japan) Mill Certification

Table 2-2: Chemical Composition from Mill Certificates

Element		Steel				
		GR345	HPS485	HT440	LYP100	LYP225
Composition %	C	0.14	0.08	0.14	0.01	0.02
	Mn	1.16	1.13	1.43	0.08	0.47
	P	0.018	0.008	0.007	0.010	0.017
	S	0.013	0.002	0.002	0.005	0.006
	Si	0.42	0.34	0.28	0.01	0.01
	Cu	0.28	0.30	-	-	-
	Ni	0.18	0.29	0.02	0.02	0.02
	V	0.039	0.053	0.04	-	-
	Cb	0.002	0.021	-	-	-
	Al	0.040	0.024	-	-	-
	Cr	0.53	0.47	0.02	0.02	0.02
	Mo	0.06	0.04	0.12	-	-
	N	0.005	-	-	0.025	0.018

Table 2-3: Measured Mechanical Properties

Property	Steel				
	GR345	HPS485	HT440	LYP100	LYP225
E MPa (ksi)	186 200 (27 000)	201 300 (29 200)	208 200 (30 200)	153 100 (22 200)	195 100 (28 300)
f_{ya} MPa (ksi)	353 (51.2)	503 (73.0)	501 (72.7)	76.5 (11.1)	242 (35.1)
f_{ua}[a] MPa (ksi)	534 (77.4)	590 (85.5)	688 (99.8)	257 (37.3)	324 (47.0)

a ultimate strength was obtained from mill certificates

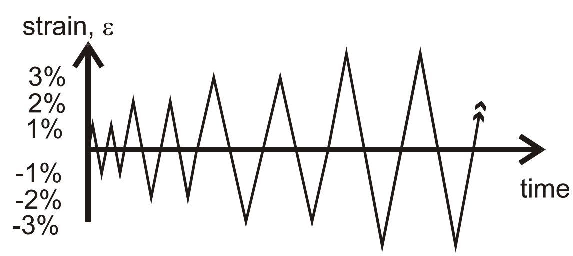
2.4 Load History

All of the tests were displacement controlled using the laser extensometer to eliminate any effects of possible grip slippage or deformations outside of the effective length. The distance between two targets placed within the effective length was measured prior to each test by the laser extensometer. The strain values were calculated during testing from the deformations measured by the laser extensometer between two targets within the effective length. The cycles were fully reversed, i.e. with strain ratio $R = \varepsilon_{min}/\varepsilon_{max} = -1$ and only varied in strain amplitude and strain rate.

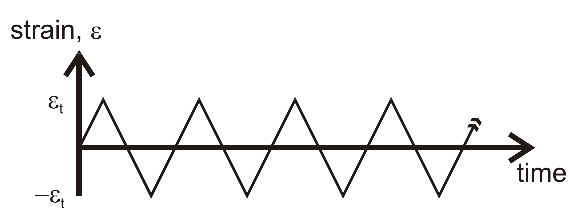
2.4.1 Strain Amplitude

Two types of triangular waveform load history were used as illustrated in Figure 2-4; incremental and constant strain amplitude. The incremental amplitude experiments were conducted using two cycles of progressively increasing amplitude and were the first sets of tests completed with the aim to explore the significance of material cyclic hardening on the observed shear link overstrength. Two cycles per amplitude were chosen to monitor the significance of cyclic hardening within the same strain range. The first two cycles were conducted at 1% total strain amplitude and increased by an additional 1% after each of the subsequent two cycles.

The constant amplitude experiments were conducted using cycles of prescribed target strain amplitude ε_t, which all started with a tensile quarter cycle. A set of inelastic strains was chosen from 1% to 7% strain amplitude. This range ensured significant plastic behavior and was representative of the magnitudes measured during the shear link tests. Failure was defined as complete fracture or a reversal point on the stress-strain curve that did not achieve 50% of the maximum recorded cyclic stress.



(a) Incremental Strain Amplitude Load History



(b) Constant Strain Amplitude Load History

Figure 2-4: Cyclic Load History Types

2.4.2 Strain Rate

The cyclic frequency of each test was set such that the strain rate remained constant. The frequency can be related to the strain rate and strain amplitude based on Equation 2-1. Working of the material during large amplitude strain demands can results in temperature increase that can affect the material properties. Typical structural components can dissipate the heat more efficiently than a coupon. In an effort to minimize the temperature gradient in the specimen, the strain rate was set to be pseudo-static at $\dot{\varepsilon} = 0.1$ *%/sec* for majority of the experiments.

$$f = \frac{\dot{\varepsilon}}{4\left(\frac{\Delta\varepsilon}{2}\right)} \quad (Hz) \tag{2-1}$$

Strains induced by seismic loads however are dynamic. In an effort to gauge the effects of strain rate, one coupon of each type of steel was subjected to cycles of 4% strain amplitude at constant strain rate of $\dot{\varepsilon} = 10$ *%/sec*. The strain amplitude was chosen as the medium of the amplitudes considered. The higher strain rate was chosen as a representative value of the strain rate expected in structural components of bridge structures. For example, consider a plastically deforming shear link in a structural system vibrating with an effective period of 2 *sec.* The plastic strains in a shear link are not axial, but uni-directional strains have been recorded in the range of 2-5% strain for link deformations at 0.08 *rad*. The average strain rate for a completely reversed 5% strain amplitude at 2 *sec* period of vibration would be 10%/sec. This rate is higher than rates expected for a steel damper for a base isolator or an unbonded brace reported to be 5%/*sec* and 2.5%/*sec* for the two systems respectively (Eiichiro et al. 1998) and provides an upper bound for expected structural dynamic behavior.

2.5 Test matrix

The study concentrated on the constant strain amplitude experiments which were used to evaluate both stress-strain as well as fatigue life of the steels. A summary of all the tests conducted is shown in Table 2-4, where "s" indicates the slower pseudo-static strain rate and "d" indicates the faster dynamic rate. In total, 45 individual coupons were tested.

Table 2-4: Summary Matrix of Reverse Cyclic Experiments

Test	Steel				
	GR345	HPS485	HT440	LYP100	LYP225
Incremental Amplitude	s	s	s	s	s

Table 2-4: Summary Matrix of Reverse Cyclic Experiments

Test		Steel				
		GR345	HPS485	HT440	LYP100	LYP225
Target Strain for Constant Amplitude ε_t	1%	s	s	s	s	s
	2%	s	s	s	s	s
	3%	s	s	s	s	s
	4%	s, d	s, d	s, d	s, d	s, d
	5%	s	s	s	s	s
	6%	s	s	s	s	s
	7%	s	s	s	s	s

SECTION 3
CYCLIC STRESS-STRAIN BEHAVIOR

3.1 Results from Incremental Strain Amplitude Tests

The steel cyclic stress-strain relationship is important in order to quantify the yield as well as the maximum stress developed for design of the structural components and associated connections. This section examines the cyclic stress-strain response of the different steels.

The incremental strain amplitude tests were conducted as an exploratory study to investigate the influence of material cyclic characteristics on the significant discrepancy among the recorded overstrengths obtained from the shear link experiments. One specimen was tested for each grade of steel. The stress-strain results from these tests are shown in Figure 3-1, where the actual yield strength from Table 2-3 is referenced using a horizontal line. The tests were conducted up to fracture except for LYP225, in which case the test was terminated after the second cycle of 5% strain because the laser beam on the extensometer was accidentally interrupted.

Hardening of the material was evident within the first two cycles for all steel grades. Cyclic hardening which is characterized by stress increase from one cycle to the next was also present for all steels except for HT440. The stress increased with larger strain amplitudes, but did so to different levels for the different steel grades. The maximum achieved resistance can be summarized by the maximum recorded stress σ_{max} normalized to the actual yield strength as shown in Table 3-1.

Table 3-1: Maximum Stress Obtained from Incremental Strain Amplitude Tests

Property	Steel				
	GR345	HPS485	HT440	LYP100	LYP225
Normalized Max. Stress Ratio σ_{max}/f_{ya}	2.1	1.5	1.5	5.3	2.0

The trends observed in the stress-strain response were similar to the trends in overstrengths observed for the shear link specimens made from those grades of steel. For example, GR345 and LYP225 had similar maximum stress ratio magnitudes. In the shear link experiments, Link C345a and Link L225 had similar overstrength magnitudes. The lowest ratio was recorded for HPS485, while the largest was for LYP100 similar to the trends in overstrength for Links H485 and L100 respectively. Based on these results, a more comprehensive study using constant amplitude strain tests was conducted for the different steels.

3.2 Results from Constant Strain Amplitude Tests

Discussions of the test results from the constant amplitude tests were divided into two categories based on the previously outlined expected end use; structural grade steels and LYP steels. The structural grade steels included GR345, HPS485 and HT440, while the LYP steels were LYP100 and LYP225.

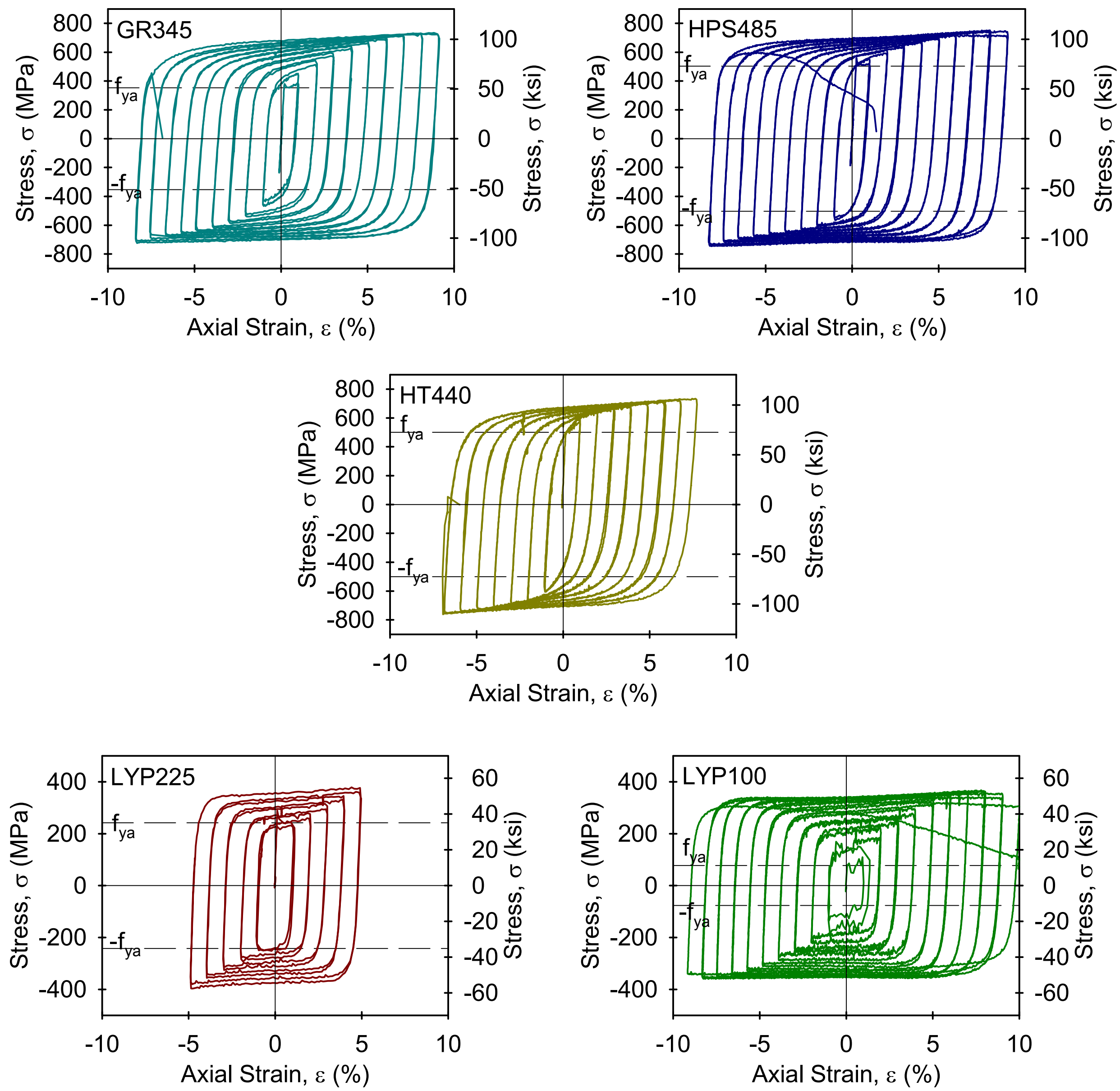


Figure 3-1: Stress-Strain from Incremental Strain Amplitude Tests

3.2.1 Cyclic Stress-strain Response of Structural Grade Steels

The stress-strain responses obtained from the constant amplitude experiments for structural grade steels are shown in Figure 3-2 through to Figure 3-4 for all considered strain amplitudes. Strength degradation occurred prior to failure for target amplitudes below $\varepsilon_t = 3\%$. The degradation was caused by a crack that propagated through the section and reduced the effective cross sectional area. For strain amplitudes higher than 3%, the progression from crack propagation to failure often occurred within the same half cycle for GR345 and HT440. HPS485 steel exhibited gradual degradation even for amplitude strains of 3% and 4%, which may be attributed to the higher toughness inherent in high performance steels.

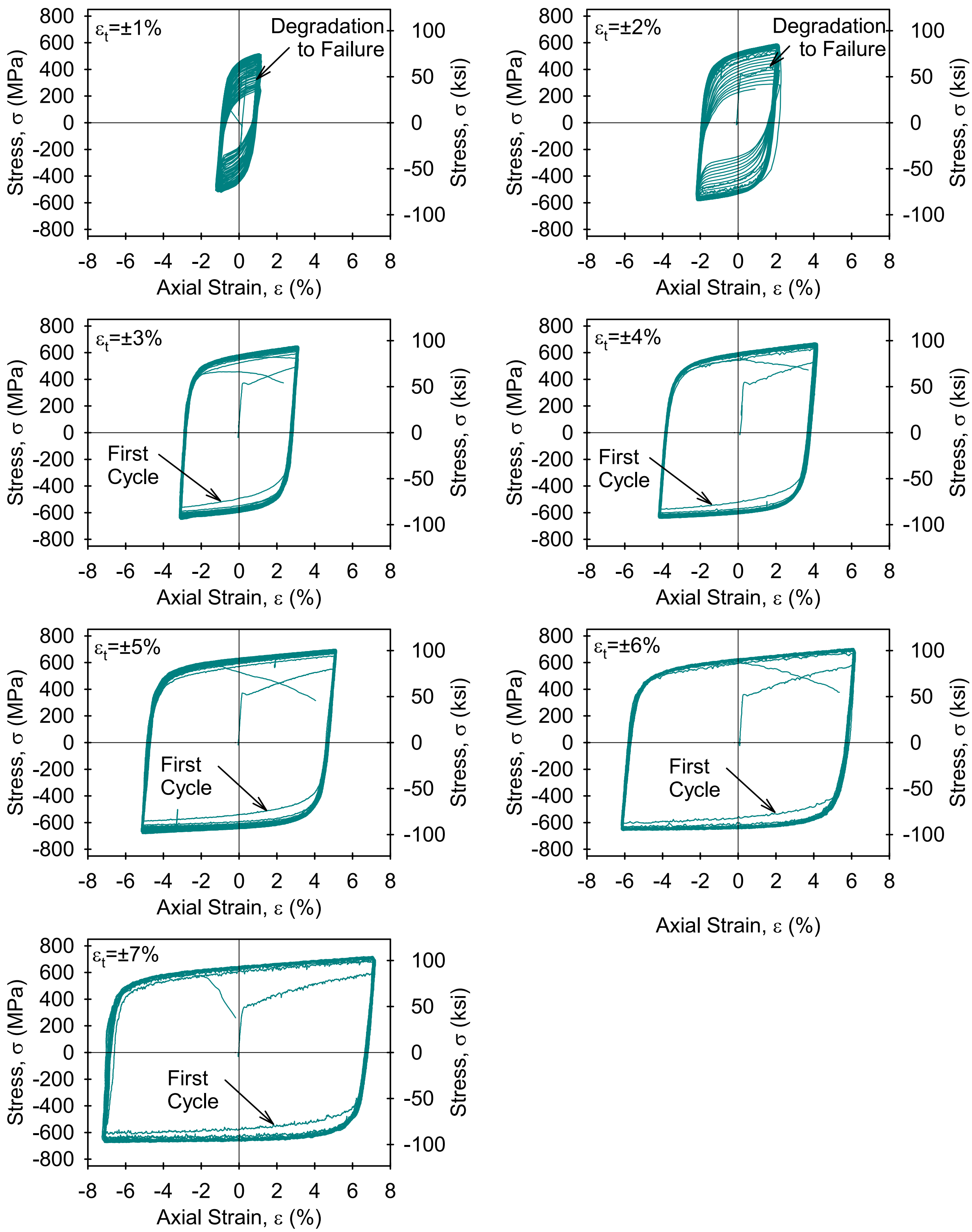


Figure 3-2: Stress-Strain Response of GR345 Coupons

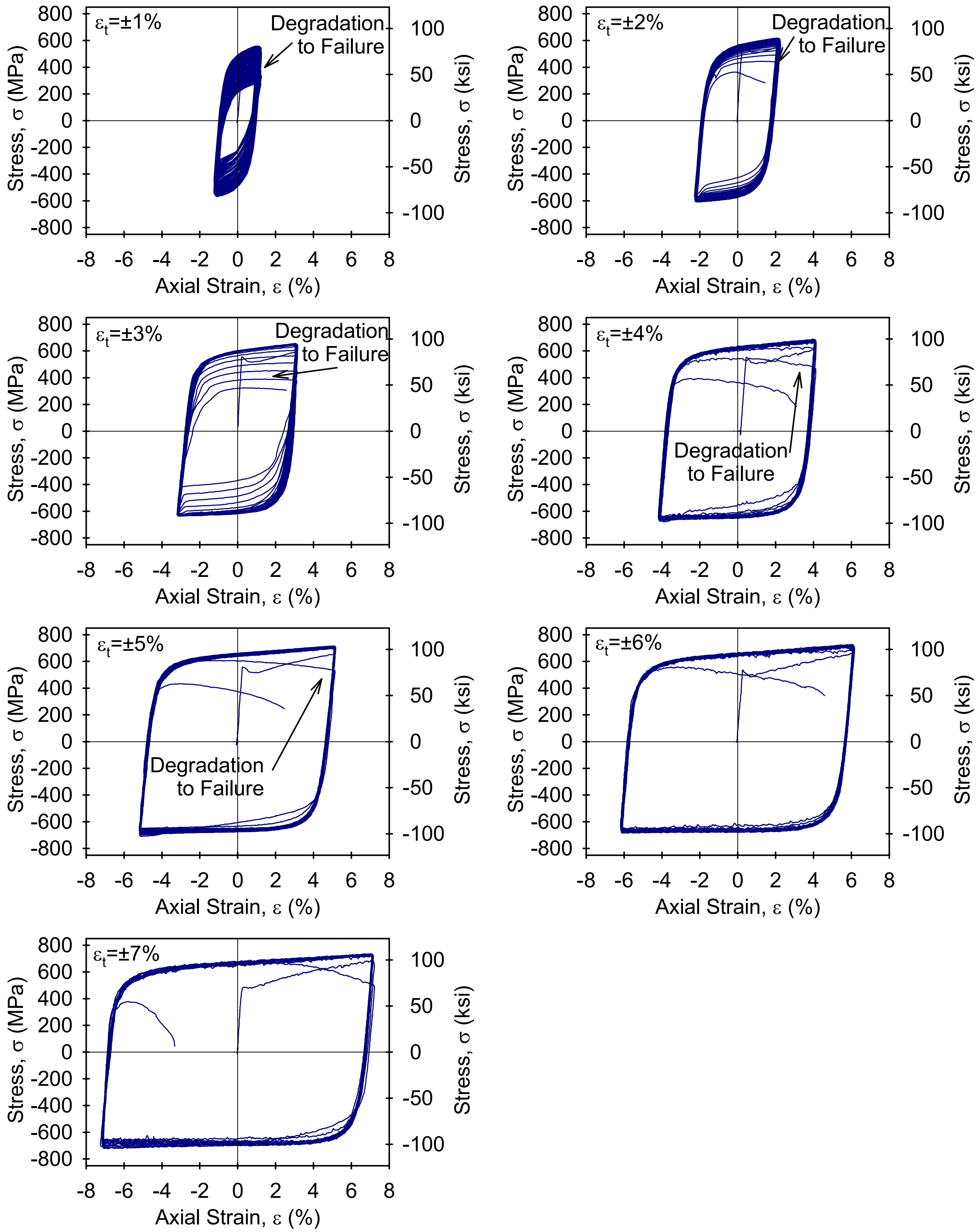


Figure 3-3: Stress-Strain Response of HPS485 Coupons

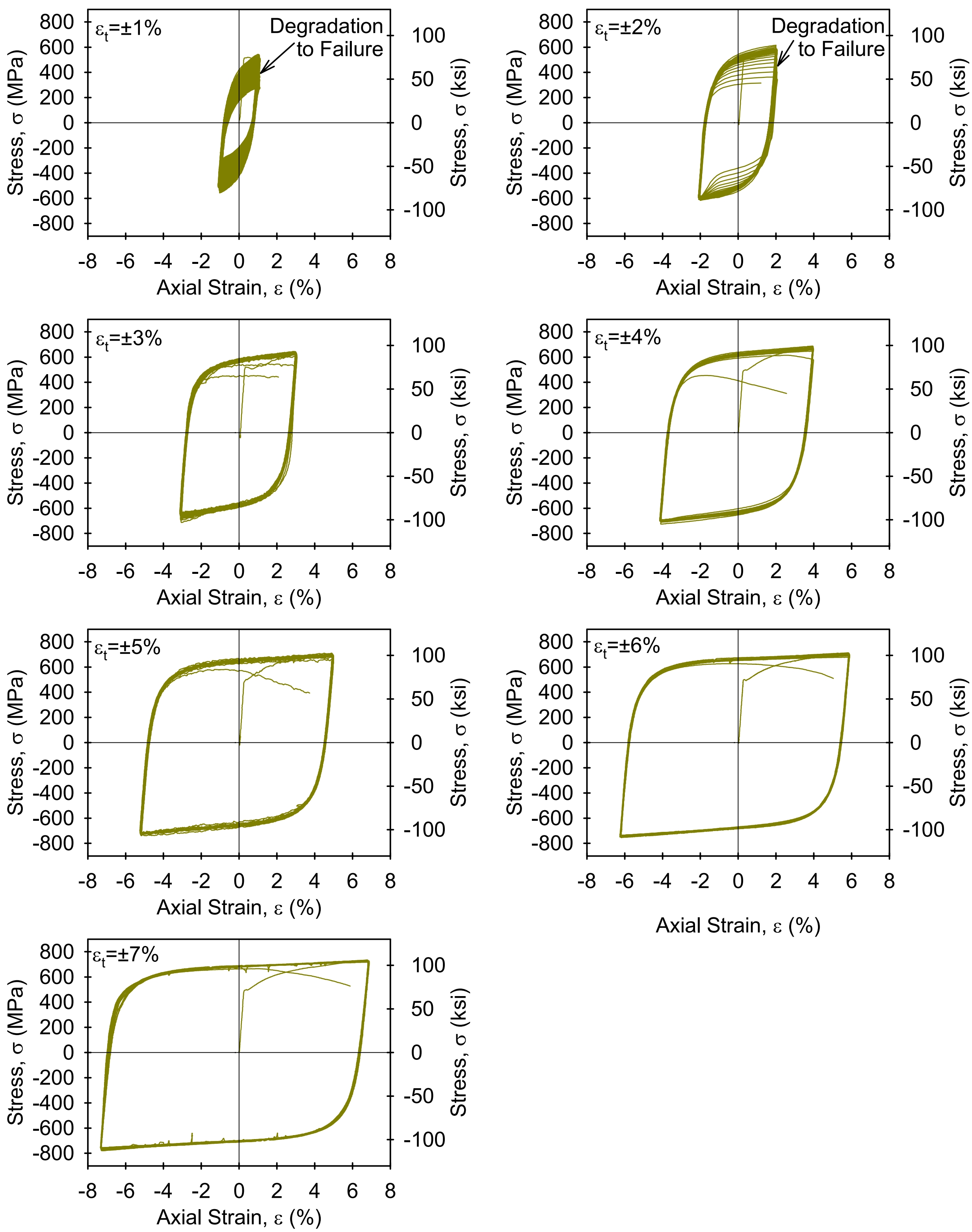


Figure 3-4: Stress-Strain Response of HT440 Coupons

In order to gauge the effect of cyclic loading on the stress strain response, the cyclic behavior was contrasted to the monotonic in Figure 3-5 through to Figure 3-7. The initial loading and the final degradation portions were removed for clarity. The monotonic response was obtained from the first quarter cycle of the largest amplitude strain tests. Cyclic hardening was evident by the stress increase from monotonic to cyclic response in GR345 and H485 steels. A combination of cyclic hardening and cyclic softening occurred for HT440.

The variation of stress is shown in Figure 3-8 through to Figure 3-10. The maximum stress achieved at each reversal σ_{max} is shown throughout the life of the specimen depicted by the number of reversals. For both GR345 as well as HPS485, most of the cyclic hardening occurred within the first 3 to 4 reversals. GR345 continued to steadily increase thereafter, whereas HPS485 stabilized to a nearly constant stress. The cyclic softening was evident for HT440 after an initial increase, especially for the lower strain amplitude tests.

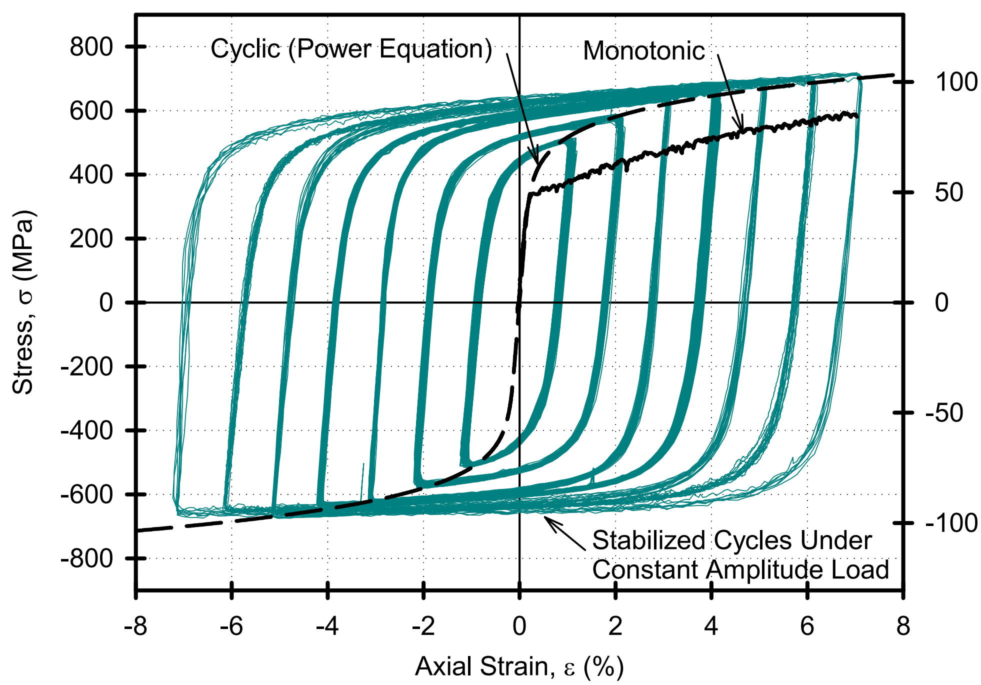


Figure 3-5: Cyclic and Monotonic Stress-strain Comparison of GR345

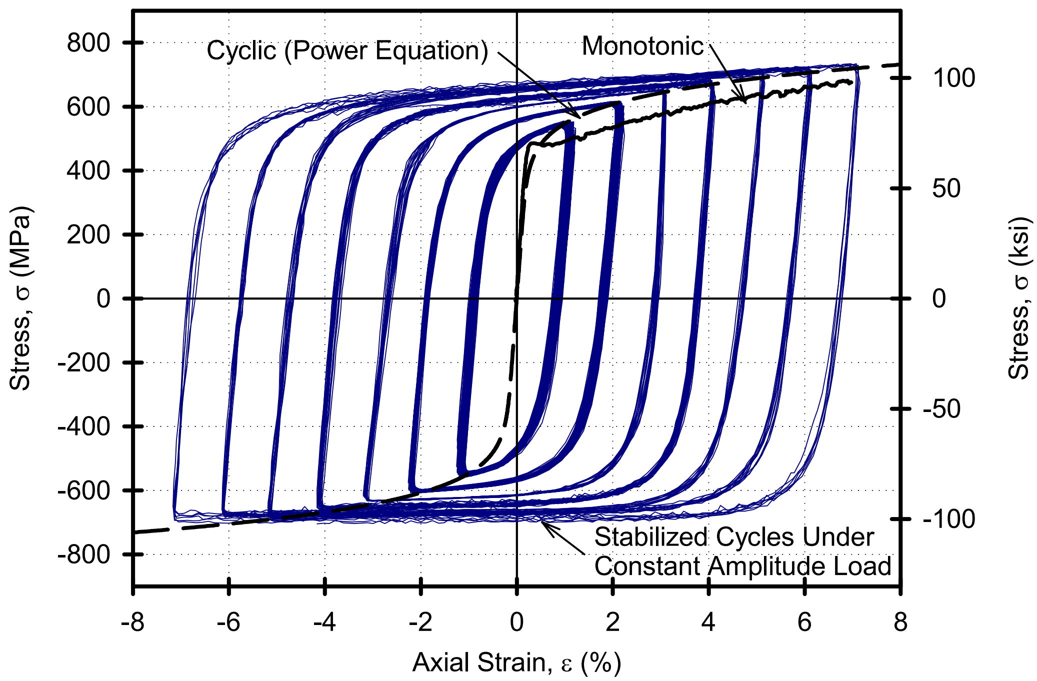


Figure 3-6: Cyclic and Monotonic Stress-strain Comparison of HPS485

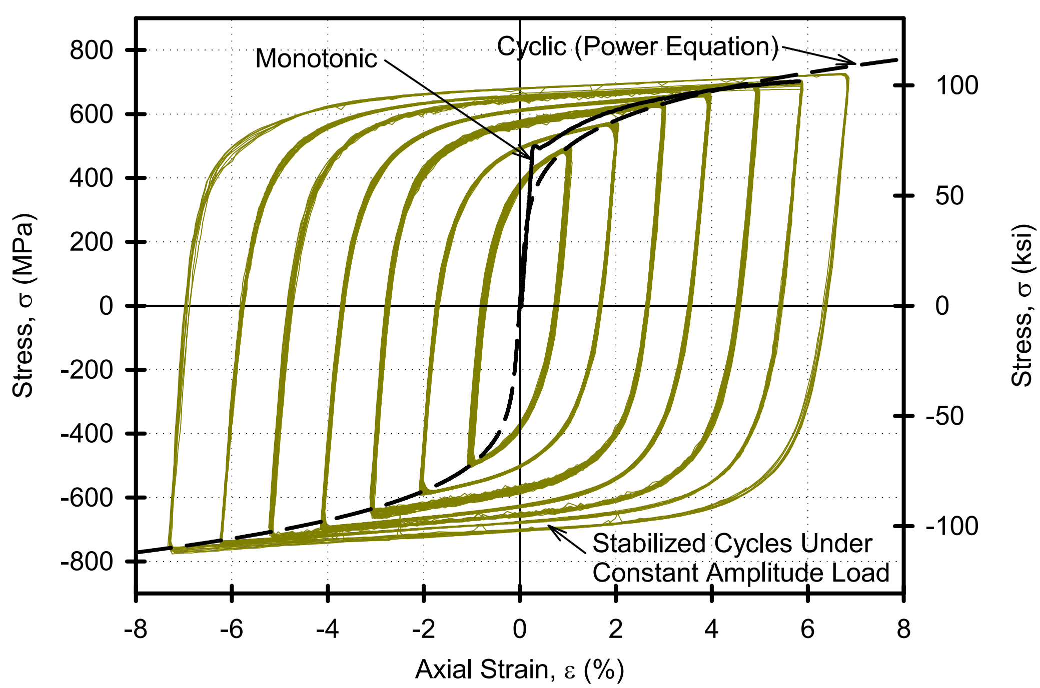


Figure 3-7: Cyclic and Monotonic Stress-strain Comparison of HT440

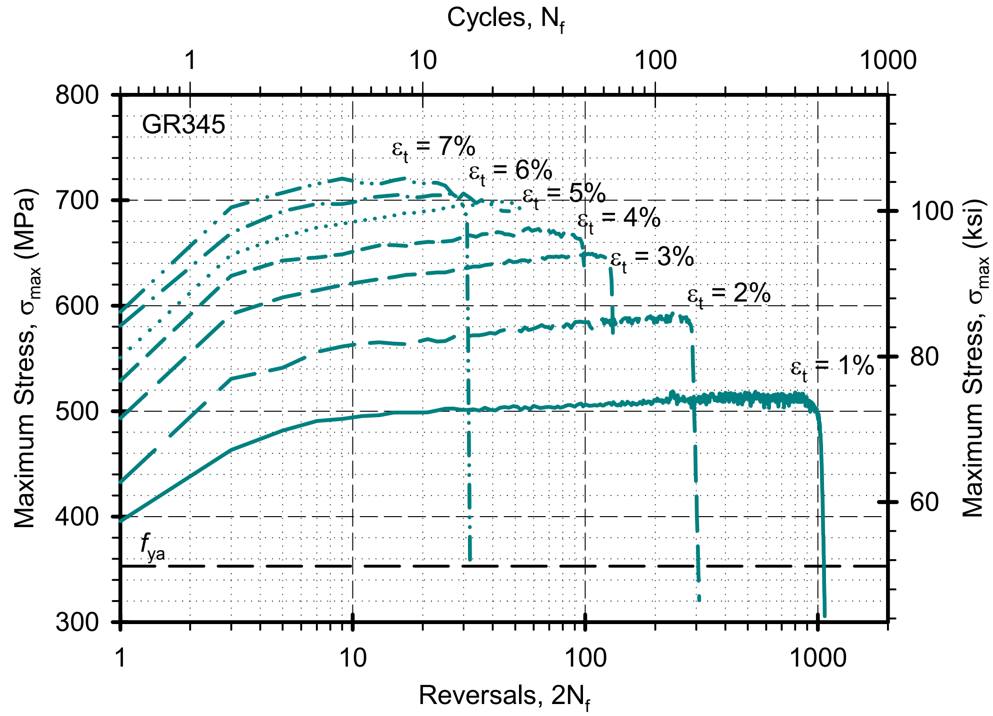


Figure 3-8: Cyclic Hardening of GR345

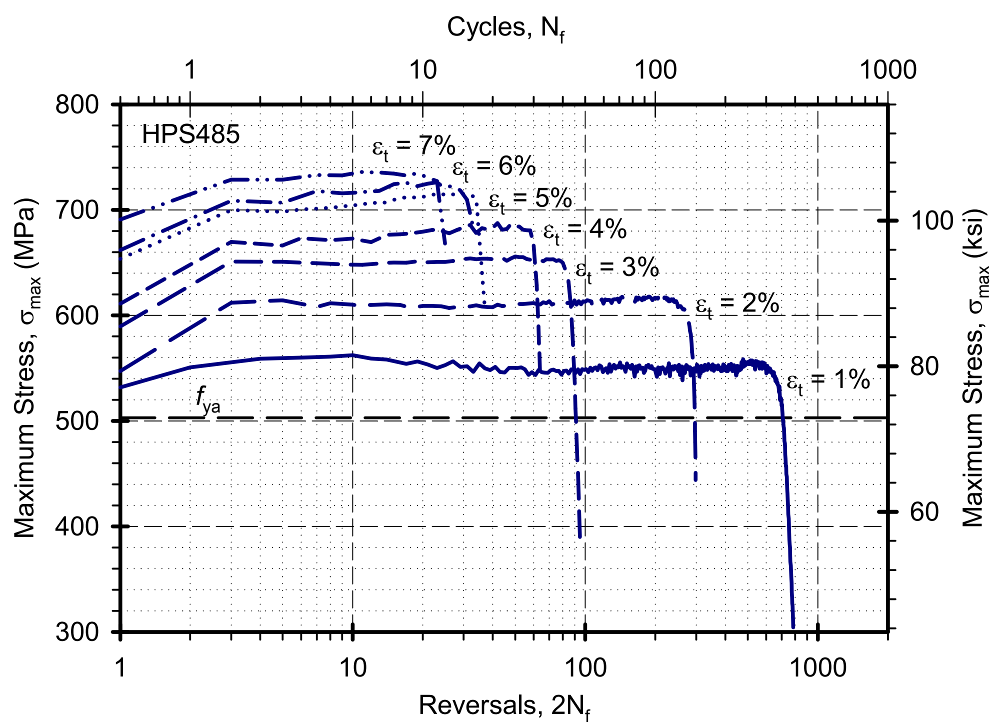


Figure 3-9: Cyclic Hardening of HPS485

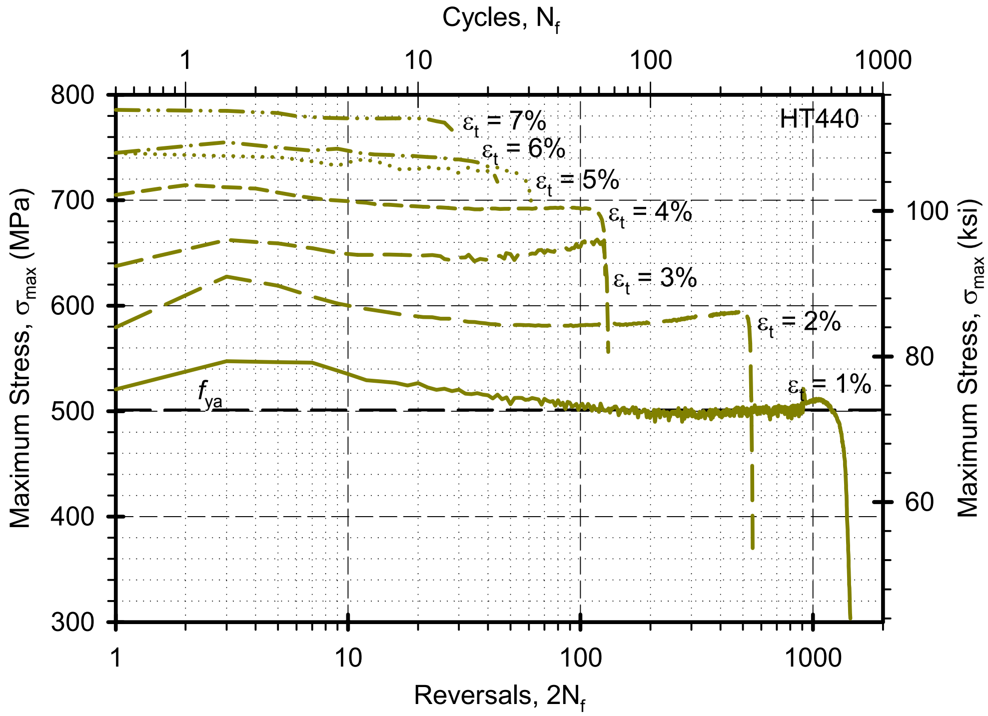


Figure 3-10: Cyclic Hardening of HT440

3.2.2 Cyclic Stress-strain Response of Low Yield Point Steels

For LYP225, three coupons were machined from a thinner 22 *mm* (0.87 *in*) plate and six from a 28 *mm* (1.10 *in*) plate. While testing the coupon made from the thinner plate at target amplitude of 5%, the specimen plastically bent about the week axis between the grips shown in Figure 3-13. The remaining two specimens of the thinner plate were tested under the smallest strain amplitudes in the test matrix at 2% and 1% successively in an attempt to reduce the effect. However, those specimens also bent after several cycles as shown in Figure 3-14. As a result, these tests were terminated prior to reaching failure, but did provide sufficient data for the initial cyclic hardening. The buckling behavior did not occur for coupons made from the thicker 28 *mm* (1.1 *in*) plate.

The stress-strain response obtained from the constant amplitude experiments for LYP100 and LYP225 steels are shown in Figure 3-11 and Figure 3-12 respectively for all strain amplitudes. The stress-strain response during the monotonic part of the history, i.e. for the very first quarter cycle, was significantly different for the two LYP steel grades when compared to the structural grade steels and also when compared to each other. The initial yield of LYP100, which was significantly lower than the specified 100 *MPa* (14.5 *ksi*), was followed by a nearly linear stress increase of an approximate linear slope of 2500 *MPa* (370 *ksi*) up to the target amplitude. The initial yield of LYP225 was found to peak at 20-25% higher than its measured yield at 0.2% offset. After the peak, the stress followed a flat or at times decreasing stress up to approximately 2% strain. For target strain amplitudes larger than 2% strain, the stress again started to increase.

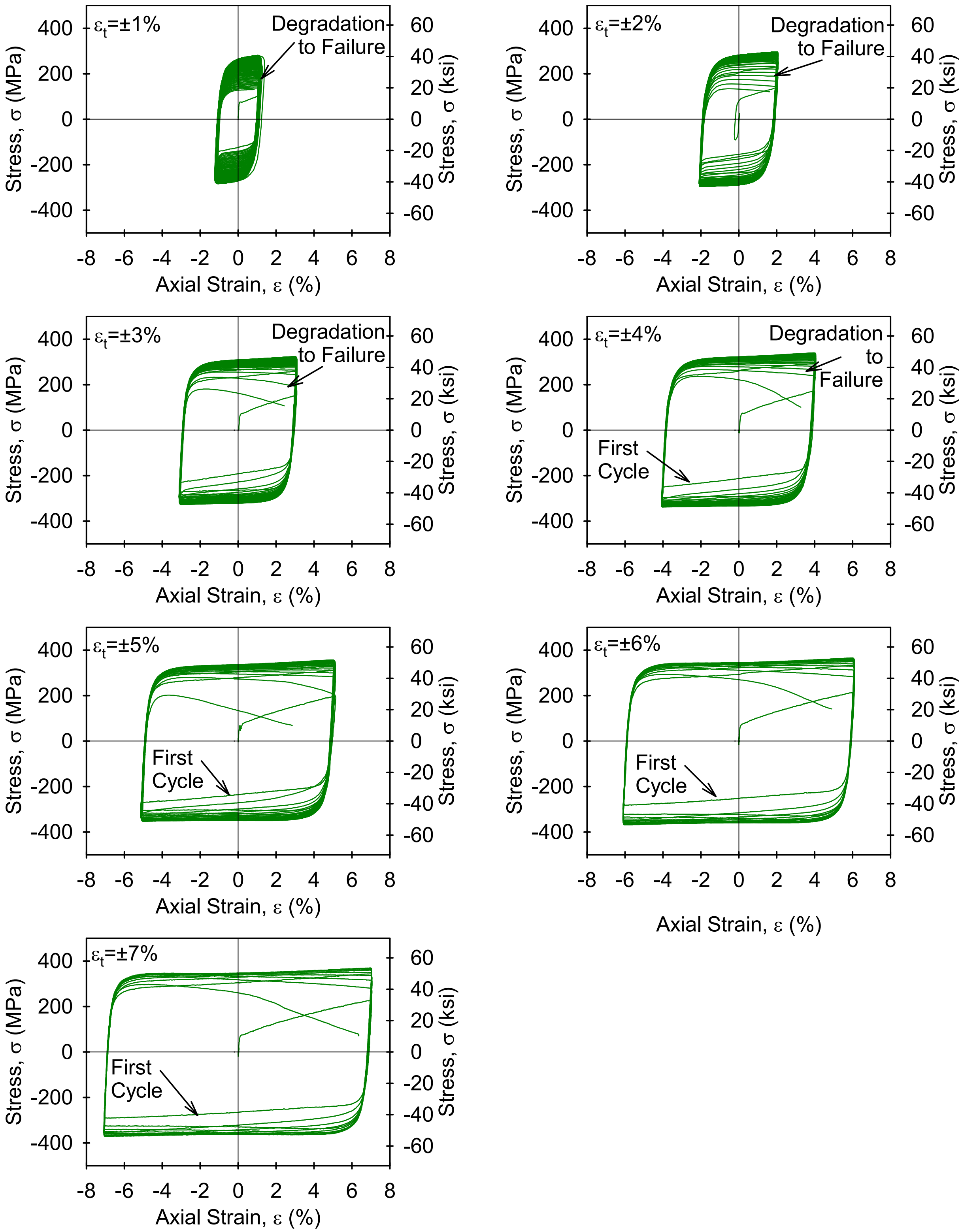


Figure 3-11: Stress-Strain Response of LYP100 Coupons

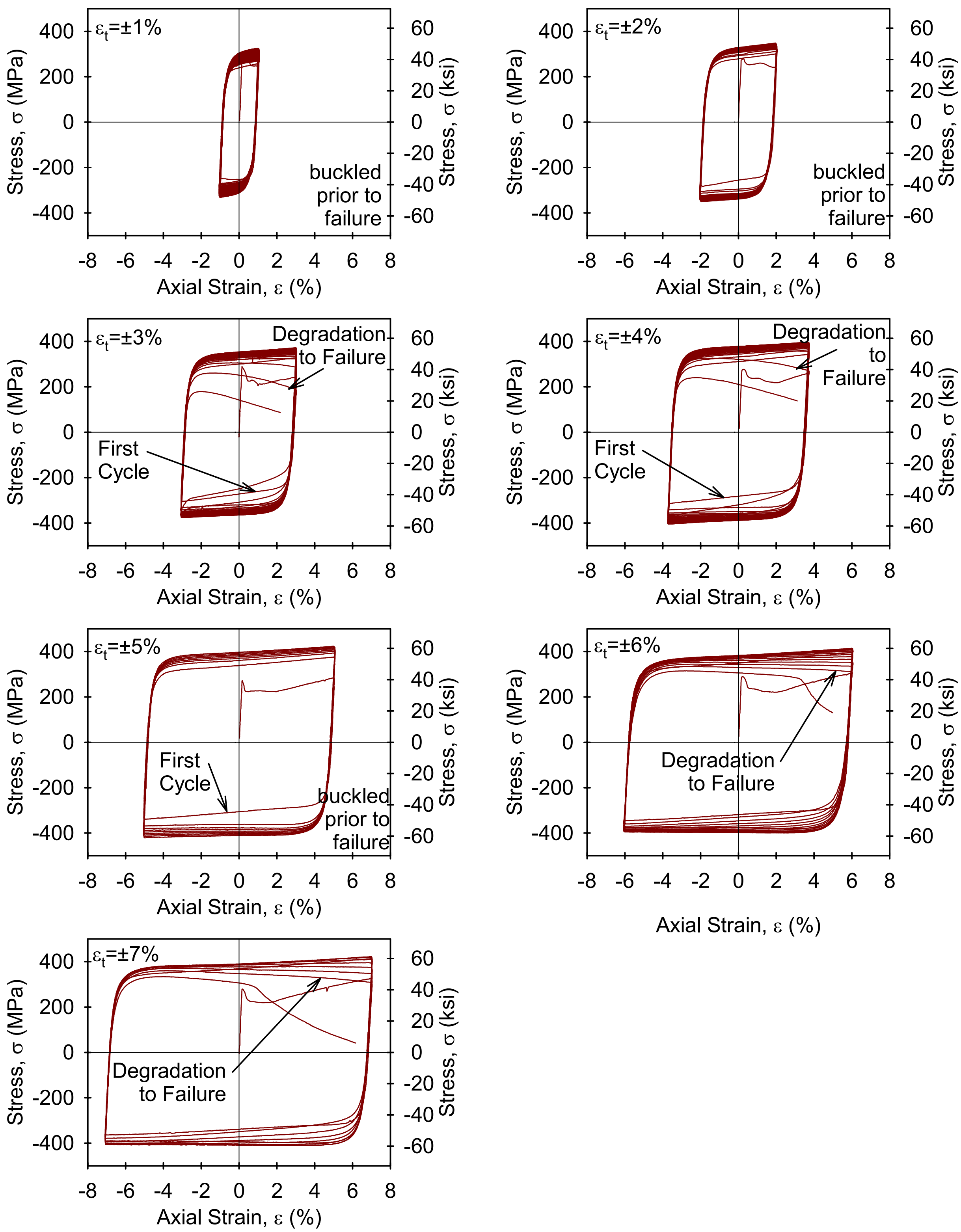


Figure 3-12: Stress-Strain Response of LYP225 Coupons

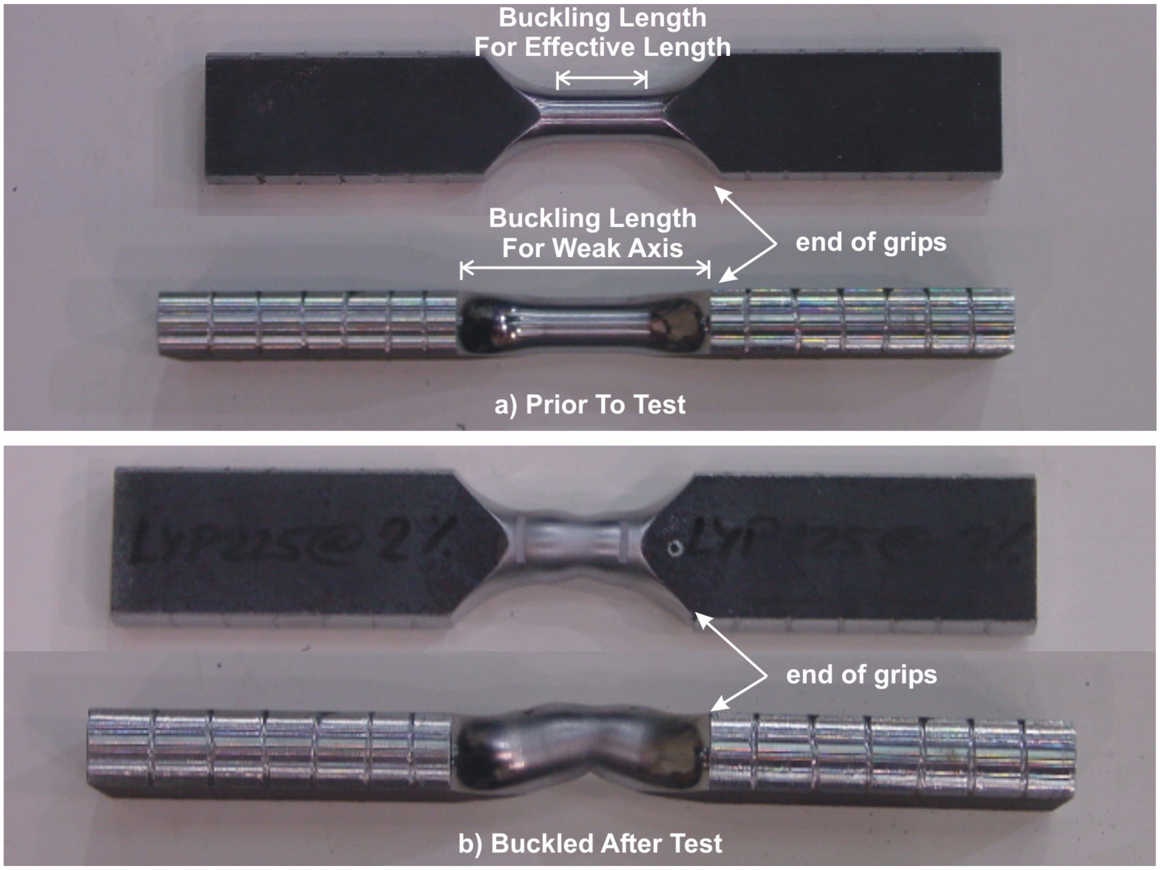


Figure 3-13: Coupon LYP225 Tested to 2% Target Strain Amplitude

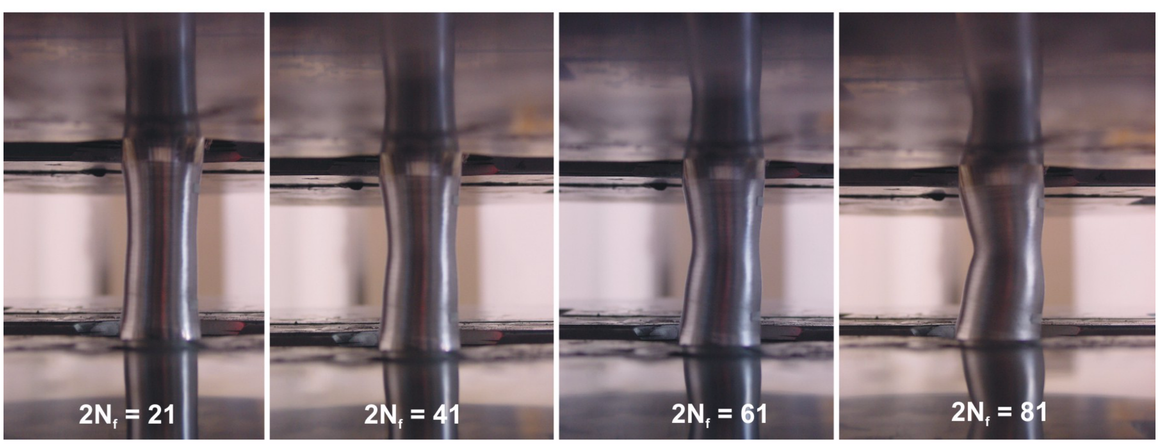


Figure 3-14: Deformation of Coupon LYP225 Tested to 2% Target Strain Amplitude

Cyclic hardening occurred in both LYP steels. The first cycle could be clearly identified by the lower stress values from the subsequent cycles. Unlike the structural grade steels, the response did not stabilize, but continued to increase with each cycle until degradation of the response started to occur. The degradation in

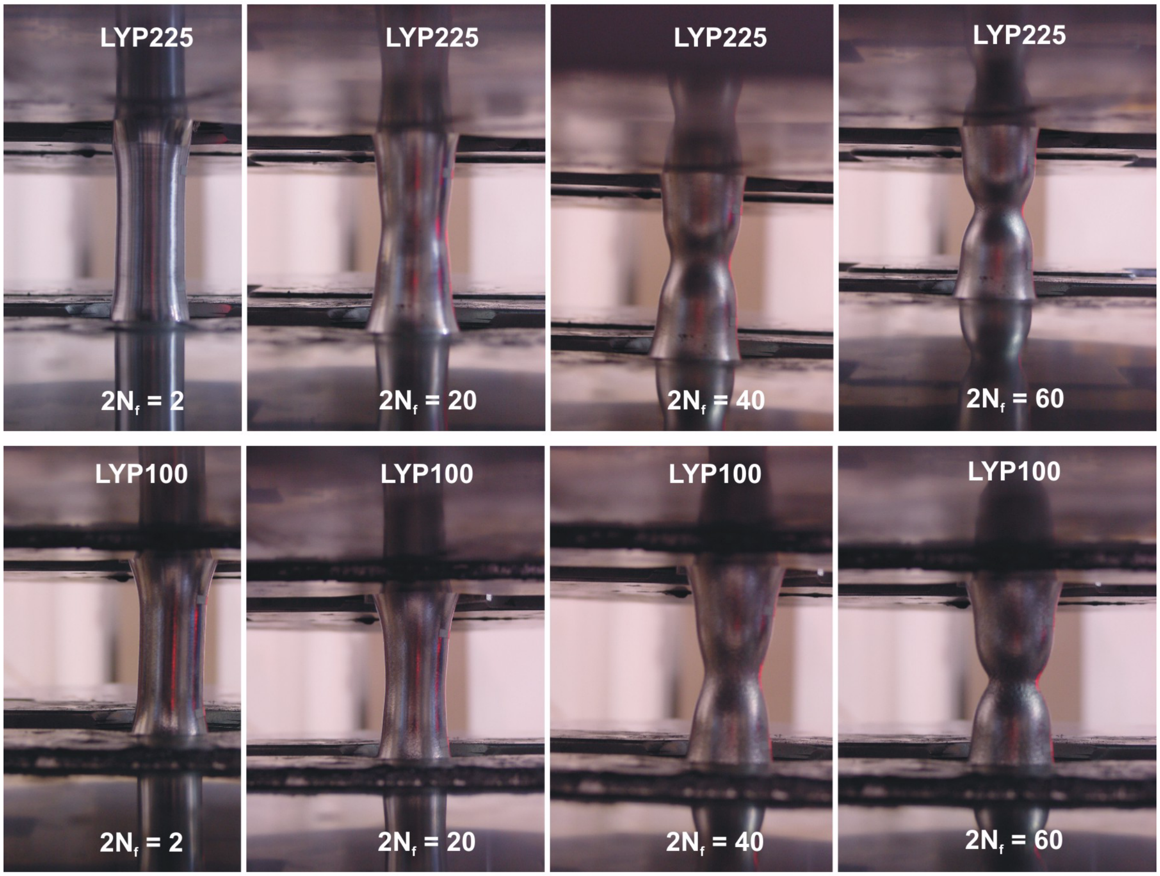


Figure 3-15: Progressive Necking in LYP Steels (4% Strain Target Amplitude Shown)

both LYP steels was caused by progressive localized reduction in diameter prior to complete section fracture. Figure 3-15 illustrates this progressive necking with increasing reversals for target amplitude of 4% strain. This behavior was observed to be more severe for LYP100 than for LYP225 and was not observed for the structural grade steels. Consequently, the resistance gradually degraded prior fracturing the section.

In order to gauge the effect of cyclic loading, the cyclic response was contrasted to the monotonic in Figure 3-16 and Figure 3-17 for LYP225 and LYP100 respectively. The initial loading and the final degradation portions were removed for clarity. The cyclic stress was always higher than the monotonic. The variation of stress throughout the life of the coupon is shown in Figure 3-18 and Figure 3-19. Majority of the cyclic hardening occurred within the first several cycles, but due to the combination of cyclic hardening and gradual strength degradation the LYP steels did not stabilize.

3.3 Power Law Cyclic Stress-Strain Relationships

The cyclic stress-strain relationship was idealized using Equation 1-6. The required power function coefficients, which are summarized in Table 3-2, were obtained from data regression of the coupon stress and plastic strain data. The data points were taken as an average of the reversal point values from the stabilized hysteretic response for the structural grade steels. However, since LYP steel hysteresis did not stabilize, the stress at half-life was used.

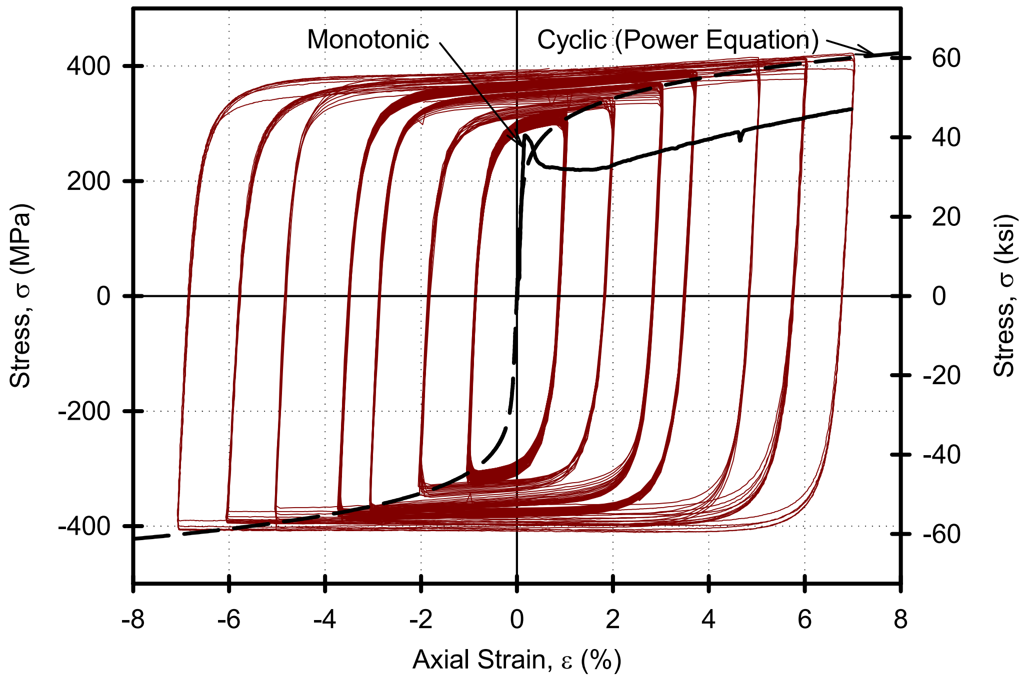


Figure 3-16: Cyclic and Monotonic Stress-strain Comparison of LYP225

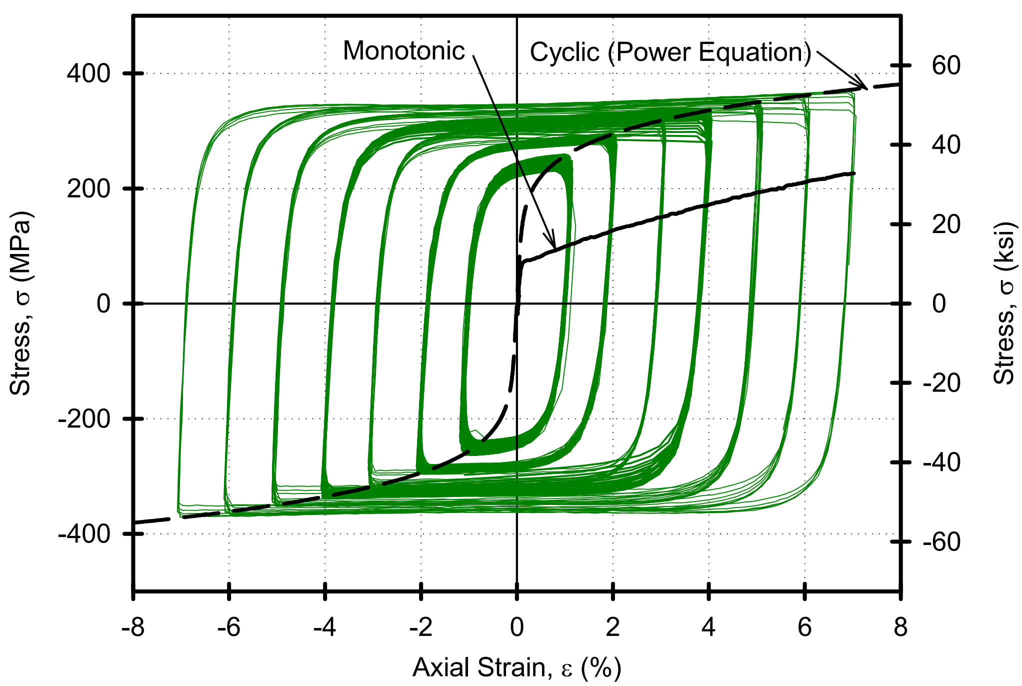


Figure 3-17: Cyclic and Monotonic Stress-strain Comparison of LYP100

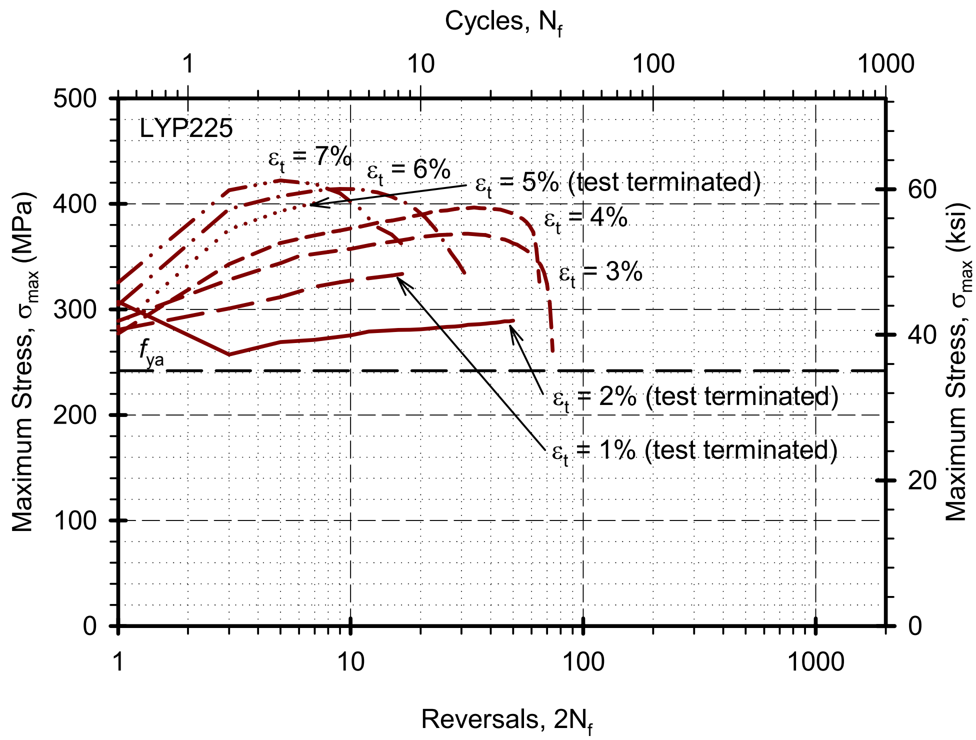


Figure 3-18: Cyclic Hardening of LYP225

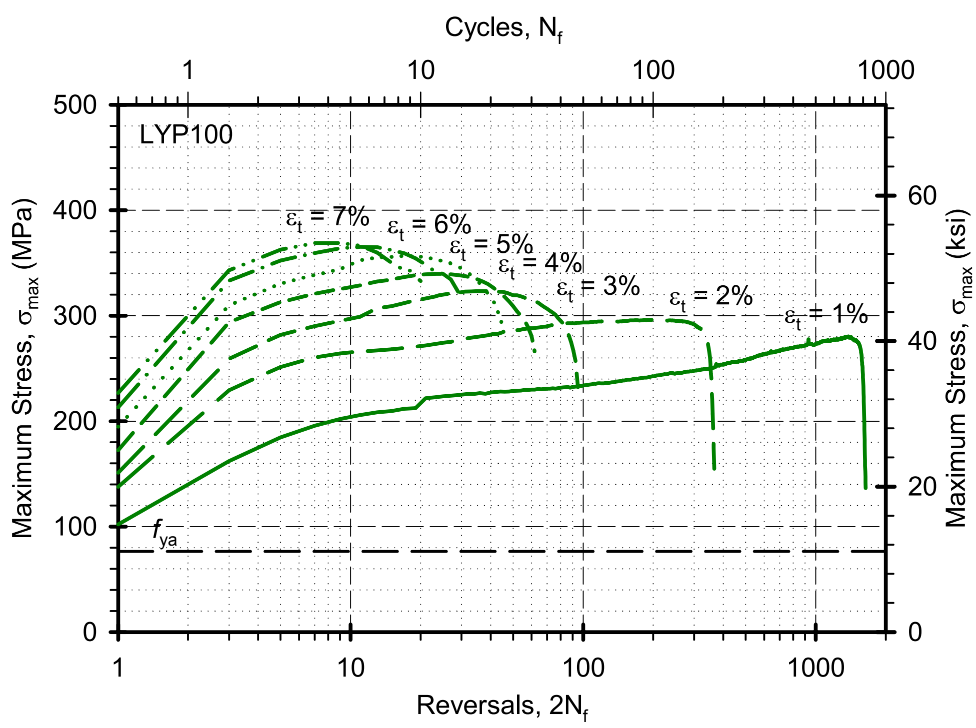


Figure 3-19: Cyclic Hardening of LYP100

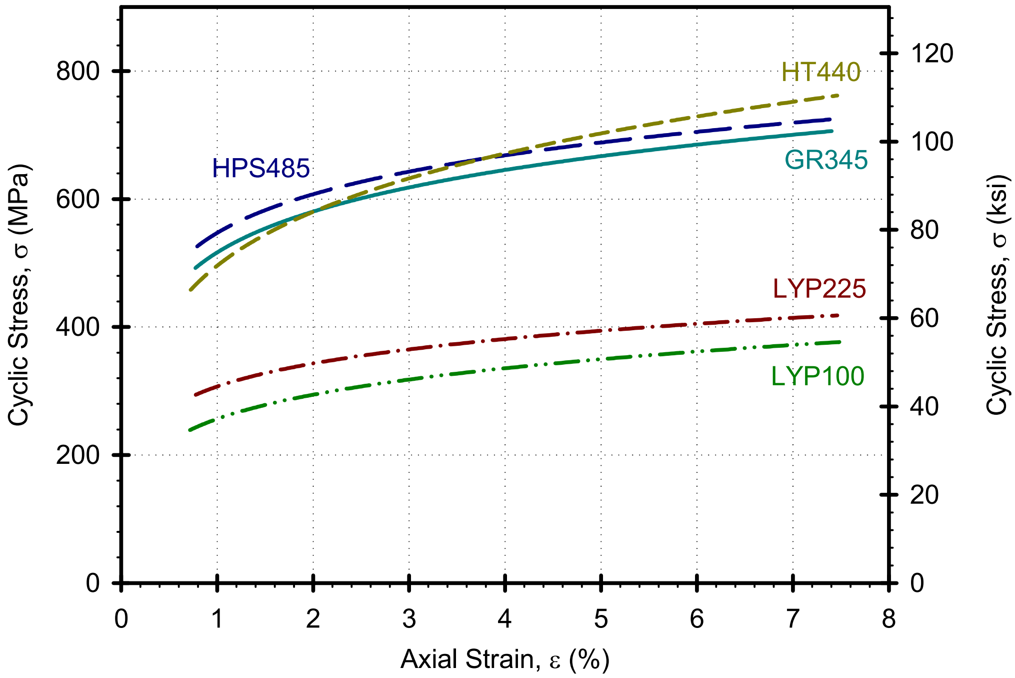


Figure 3-20: Cyclic Stress-Strain Comparison for All Steel Grades

The stress-strain cyclic relationship described by the power equation was compared to the recorded response at different target strain amplitudes in Figure 3-5 to Figure 3-7 for the structural grade steels and Figure 3-16 and Figure 3-17 for the low yield point steels. Since the curve was developed from cyclic reversal points, the curve was effective in approximating the peaks of the cyclic response. However, the relationship is not suitable for describing the monotonic response and subsequently the first quarter cycle response.

Comparison of the cyclic stress-strain response of the various steel grades was made in Figure 3-20. The structural grade steels were found to have similar relationship, despite GR345 having significantly lower yield strength. This was especially evident for the A709 grade steels, where the cyclic stress for GR345 was within 5% of the cyclic stress of HPS485 between 1% and 7% strain amplitude. Given the lower yield strength of LYP steels, the cyclic stress was also lower than the structural grades. However, despite the large difference in initial yield for the two different LYP grades, the cyclic stress of LYP100 was within 15% of LYP225 in the strain range considered.

Table 3-2: Stress-Strain Power Function Coefficients

Coefficient	Steel				
	GR345	HPS485	HT440	LYP100	LYP225
Cyclic Strain Coefficient K, MPa (ksi)	1020 (148)	1010 (146)	1270 (184)	600 (87.1)	610 (88.4)
Cyclic Strain Hardening Coefficient, n	0.138	0.124	0.192	0.178	0.144

3.4 Cyclic Stress Factor

Yield strength has traditionally been the primary material characteristic used for the design of structural components. The cyclic stress was normalized to the actual yield strength f_{ya} in Figure 3-21. This ratio, which is expressed in Equation 3-1 where σ_c is the cyclic stress, resulted in a measure of the stress increase from the design yield stress that can be expected in structural components undergoing inelastic cyclic deformations.

$$R_c = \sigma_c / f_{ya} \tag{3-1}$$

The power-law cyclic relationship of Equation 1-6 requires iterative methods of obtaining σ_c and thereby R_c for a specific value of strain. Table 3-3 lists values of R_c for the different steel grades. The highest cyclic hardening was observed in LYP100, reaching 3.4 times the yield strength at just 1% amplitude and 4.8 times the yield strength for the maximum considered amplitude. Since the other steels normalized were significantly lower than LYP100, they are shown separately in Figure 3-22. GR345 exhibited significantly larger increase than any of the structural grade steels and also larger than LYP225. The stress reached 1.45 times the yield at 1% amplitude and 2.0 times the yield strength at the maximum considered amplitude of 7%. From these results, the cyclic stress-strain relationships were highly dependant on the grade of steel as well as the amplitude of the strain.

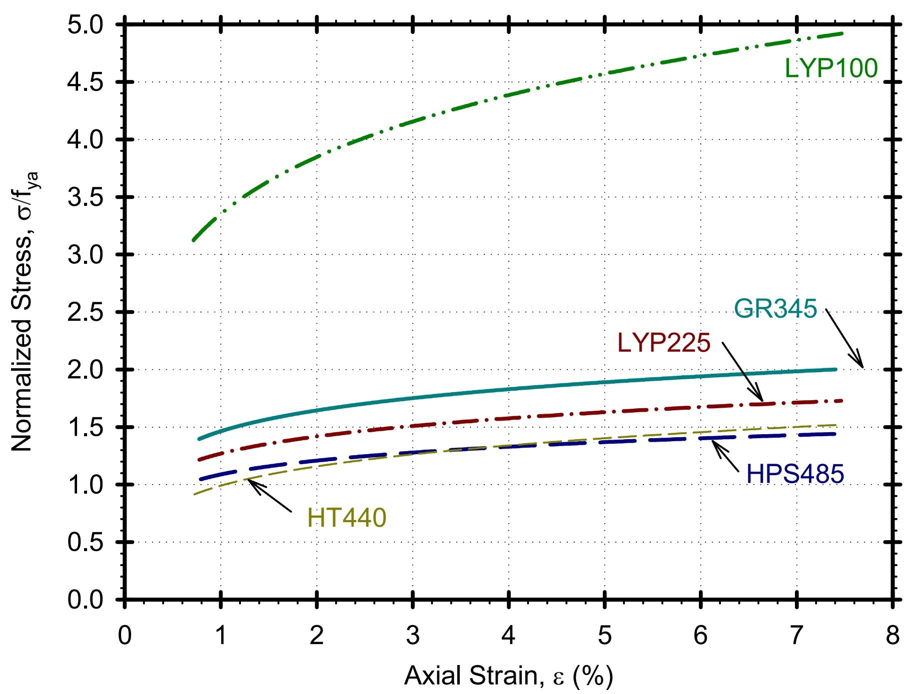


Figure 3-21: Normalized Cyclic Stress-Strain Comparison for All Steel Grades

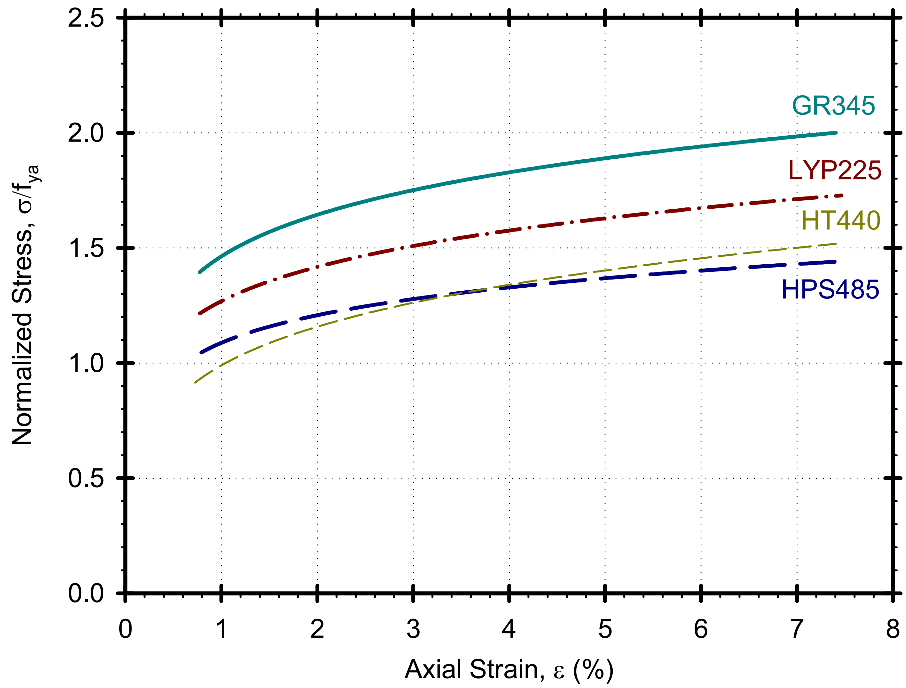


Figure 3-22: Normalized Cyclic Stress-Strain Comparison

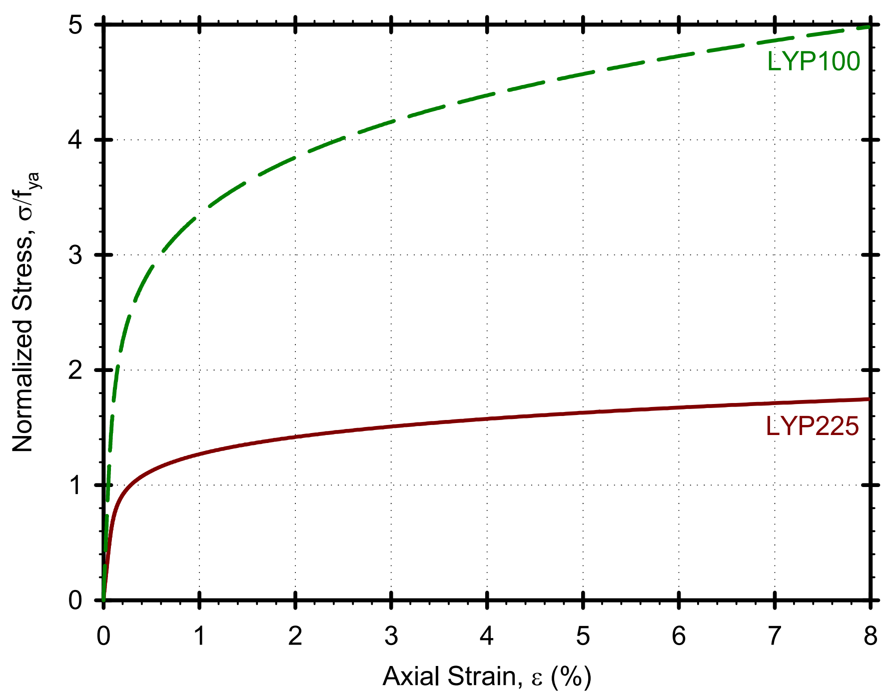


Figure 3-23: Normalized Cyclic Stress-Strain Comparison of Low Yield Point Steels

Table 3-3: Cyclic Stress Factors at Different Strain Levels

R_c at strain	Steel				
	GR345	HPS485	HT440	LYP100	LYP225
ε = 1%	1.46	1.09	0.99	3.35	1.23
ε = 2%	1.64	1.21	1.16	3.84	1.42
ε = 3%	1.75	1.28	1.26	4.15	1.51
ε = 4%	1.83	1.33	1.34	4.38	1.56
ε = 5%	1.89	1.37	1.40	4.57	1.63
ε = 6%	1.94	1.40	1.45	4.73	1.67
ε = 7%	1.98	1.43	1.50	4.86	1.71

3.5 Effect of Strain Rate on Stress-Strain Response

The dynamic tests conducted at 10 %/*s*, i.e. at 100 times faster rate than the pseudo-static, were conducted only for the target strain amplitude of $\varepsilon_t = \pm 4\%$. Because of the dynamic nature of the experiments, the load frame over achieved the target deformations because the feedback signal from the load frame did not modify the command signal in time. Even after modifying the input signal to lower than desired value, the achieved strain amplitude achieved during the tests was still ±4.4% strain and did not match exactly the pseudo-static strain amplitude. Significant heat developed during the high strain rate tests on the structural grade steels prior to failure. The heat was not measured, but was sufficient to discolor the metal to dark blue. Such high temperature gradient was not observed for the LYP steels, which were warm but could be handled with bare hands immediately after the test.

The stress-strain results for the first two cycles of the dynamic tests are contrasted to the pseudo-static response for similar amplitudes in Figure 3-24. For structural grade steels, the dynamic response during the first quarter cycle followed closely the pseudo-static curve, only rounding the initial yield peaks. The stress at first reversal was generally higher for the dynamic test except for GR345 and HT440. The peak at the initial yield observed for LYP225 during the pseudo-static tests was not as pronounced under dynamic loading. For LYP100, the response was consistently higher starting from the yield point. The shape of the hysteresis loop and the cyclic hardening levels were also similar. The remaining cycles are shown in Figure 3-25, where the shape of the hysteretic loop and the trend in cyclic hardening observed for the pseudo-static tests for each grade of steel did not significantly change. Due to the difference in achieved strain amplitudes and the limited number of coupons tested, additional direct comparison became difficult. Nonetheless, the cyclic hysteretic behavior and the maximum cyclic stress did not appear to be significantly affected by strain rate.

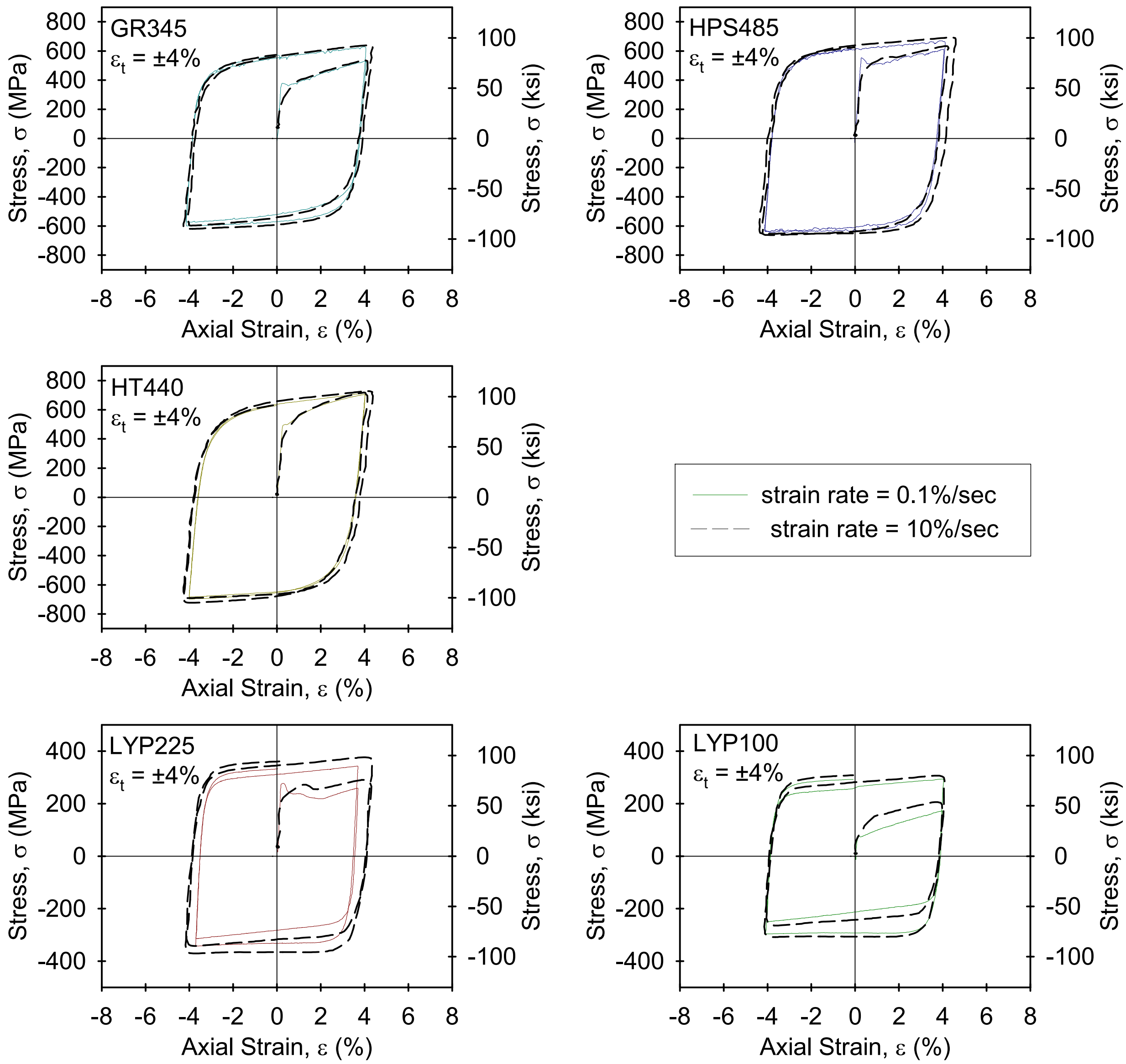


Figure 3-24: Strain Rate Effect on Stress-Strain Response for First Two Cycles

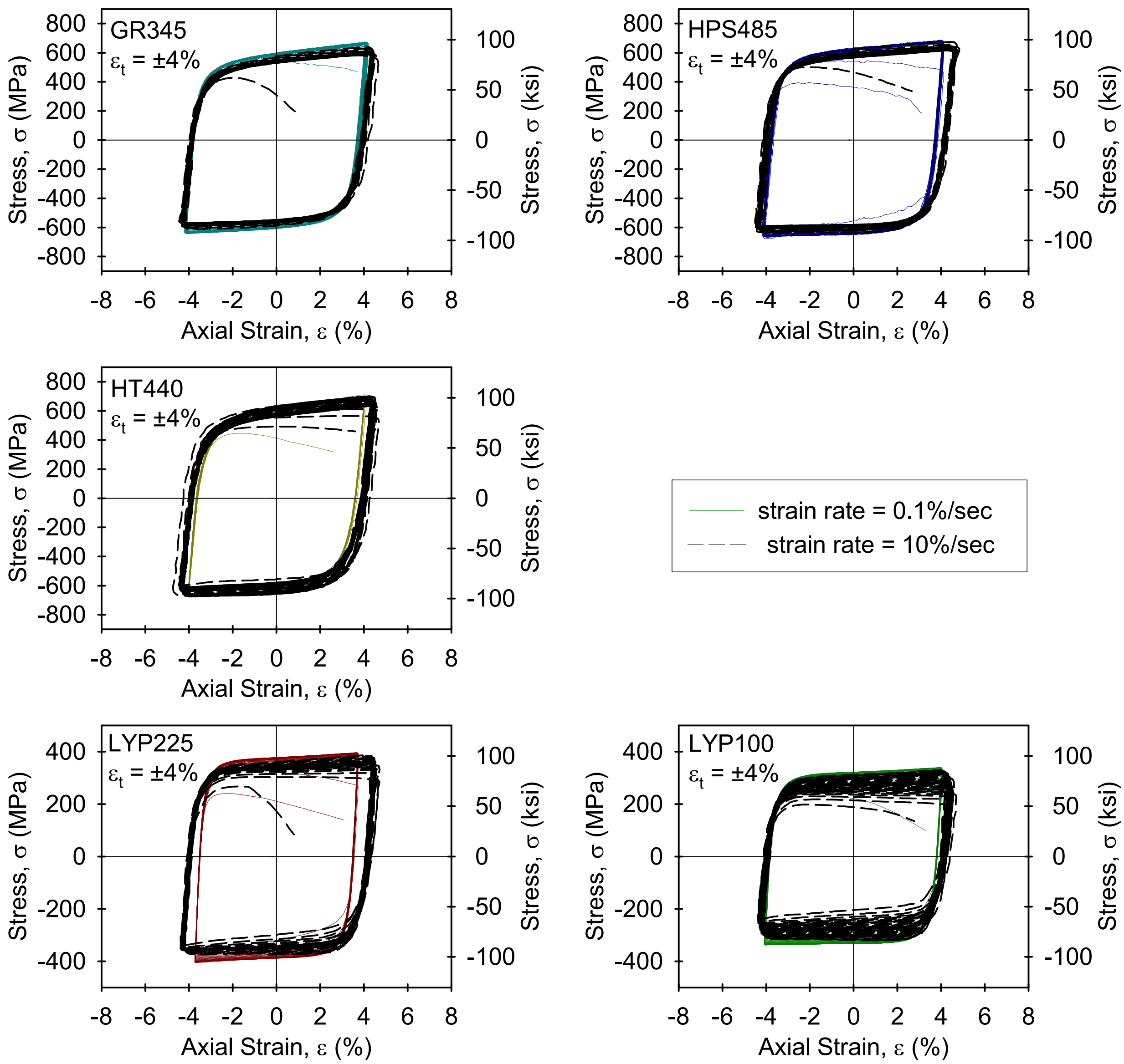


Figure 3-25: Strain Rate Effect on Stress-Strain Response After First Two Cycles

SECTION 4
LOW CYCLE FATIGUE BEHAVIOR

4.1 Recorded Fatigue Life

The low cycle fatigue data were obtained from the constant amplitude cyclic coupon tests, which were used for the stress-strain investigation and tested to ultimate failure. Table 4-1 summarizes the recorded fatigue life in terms of the achieved number of reversals prior to failure for each target amplitude. Discussion of the results was separated into structural grade steels and LYP steels.

Table 4-1: Reversals to Failure

Test		Steel				
		GR345	HPS485	HT440	LYP100	LYP225
Target Strain Amplitude ε_t	1%	1076	798	1458	1459	-
	2%	315	299	557	373	-
	3%	134	100	135	101	76
	4%	101	67	132	65	69
	5%	55	42	64	49	-
	6%	47	35	47	32	33
	7%	32	26	30	22	19

4.2 Low Cycle Fatigue of Structural Grade Steels

The fatigue strain-life results from the structural grade steel tests are shown by the discrete data points on a log-log plot in Figure 4-1. As expected, the fatigue life increased with decreasing strain amplitude. Overall, HPS485 exhibited lower fatigue life than GR345 and HT440 exhibited higher fatigue life than both of the A709 grade steels, especially for the lower strain amplitudes.

4.3 Low Cycle Fatigue of Low Yield Point Steels

The fatigue strain-life results from the tests for the LYP steels are shown by the discrete data points on a log-log plot in Figure 4-2. Only four data points were available for LYP225 due to buckling issues previously discussed for the other three specimens. For the cases considered, the fatigue life of LYP225 was found to be lower than LYP100 and also lower than the structural grade steels.

4.4 Fatigue Strain-Life Relationships

As expected for the strain amplitudes considered, plastic strains dominated the low cycle fatigue behavior. Data regression using a power function was conducted on the elastic and plastic components of the fatigue life results of each steel. The corresponding coefficients for use in the strain life relationship described by Equation 1-8 are summarized in Table 4-2.

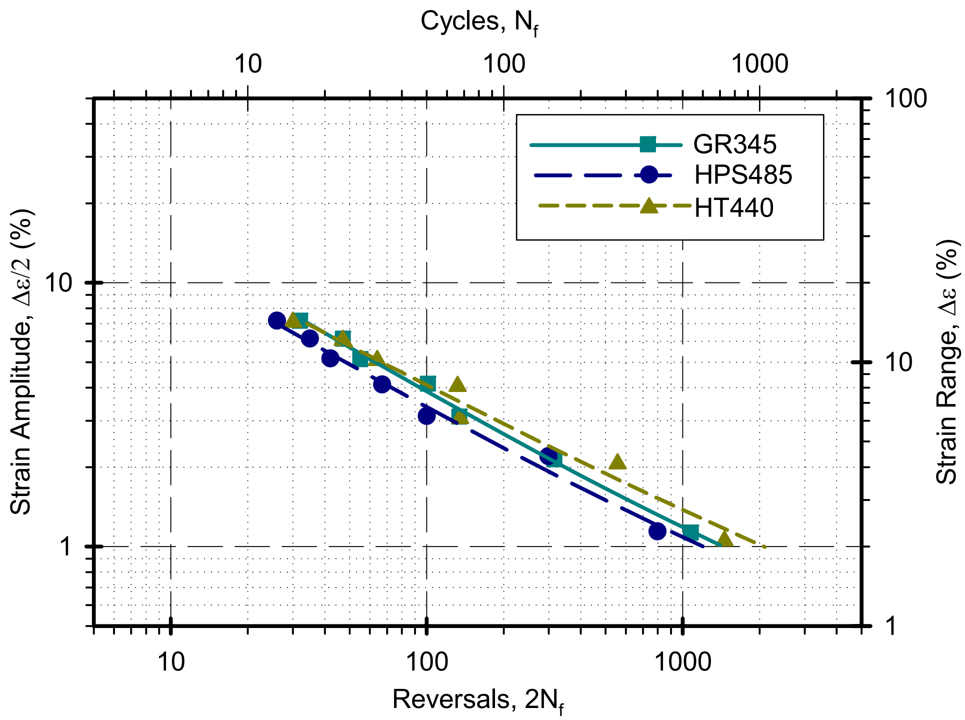


Figure 4-1: Fatigue Strain Life of Structural Grade Steels

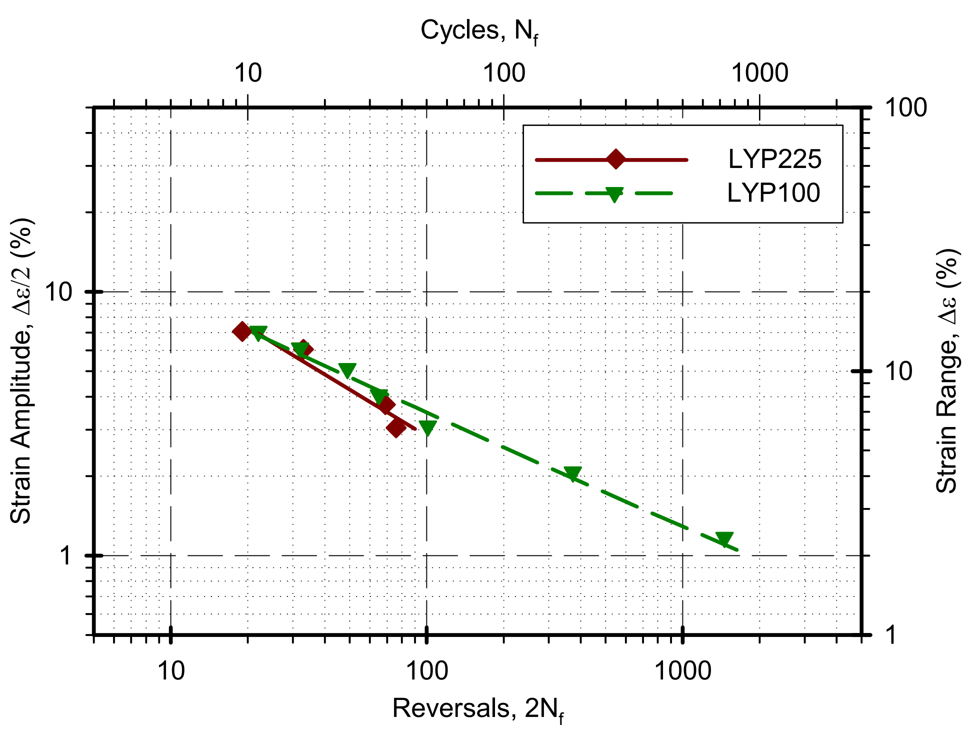


Figure 4-2: Fatigue Strain Life of Low Yield Point Steels

The relationships were compared to the discrete data in Figure 4-1 and Figure 4-2 for structural grade and LYP steels respectively. The fatigue life relationship and the recorded data show a close correlation throughout the strain amplitudes considered. The strain-life relationships for all steels were compared in Figure 4-3. Despite the noted differences, the overall fatigue strain-life for all of the grade steels showed similar behavior. Under strain control the materials can be considered to have similar life in low cycle fatigue situations such as those experienced in earthquakes.

Table 4-2: Fatigue Life Coefficients

Coefficient	Steel				
	GR345	HPS485	HT440	LYP100	LYP225
Fatigue Strength Coefficient, σ_f' *MPa* (*ksi*)	894 (130)	886 (129)	1000 (145)	475 (68.8)	507 (73.6)
Fatigue Strength Exponent, *b*	-0.082	-0.072	-0.101	-0.081	-0.063
Fatigue Ductility Coefficient, ε_f'	0.535	0.432	0.422	0.275	0.446
Fatigue Ductility Exponent, *c*	-0.590	-0.575	-0.524	-0.459	-0.612

4.5 Effect of Strain Rate on Fatigue Life

The recorded fatigue life for specimens tested using the dynamic strain rate is summarized in Table 4-3. Because the dynamic tests imposed higher strain amplitude than the pseudo-static tests, comparison was made to the calculated strain-life for the same strain amplitude, i.e. for 4.4% strain, using the coefficients from Table 4-2. Although consistently shorter life was recorded for the dynamic experiments, small difference exists between the values given that fatigue life data is typically considered on logarithmic scales.

Table 4-3: Fatigue Life for Coupons Tested Using Dynamic Strain Rate

Reversals	Steel				
	GR345	HPS485	HT440	LYP100	LYP225
Recorded Reversals to Failure, $2N_f$	61	48	78	75	55
Calculated Reversals to Failure, $2N_f$	77	59	84	60	48

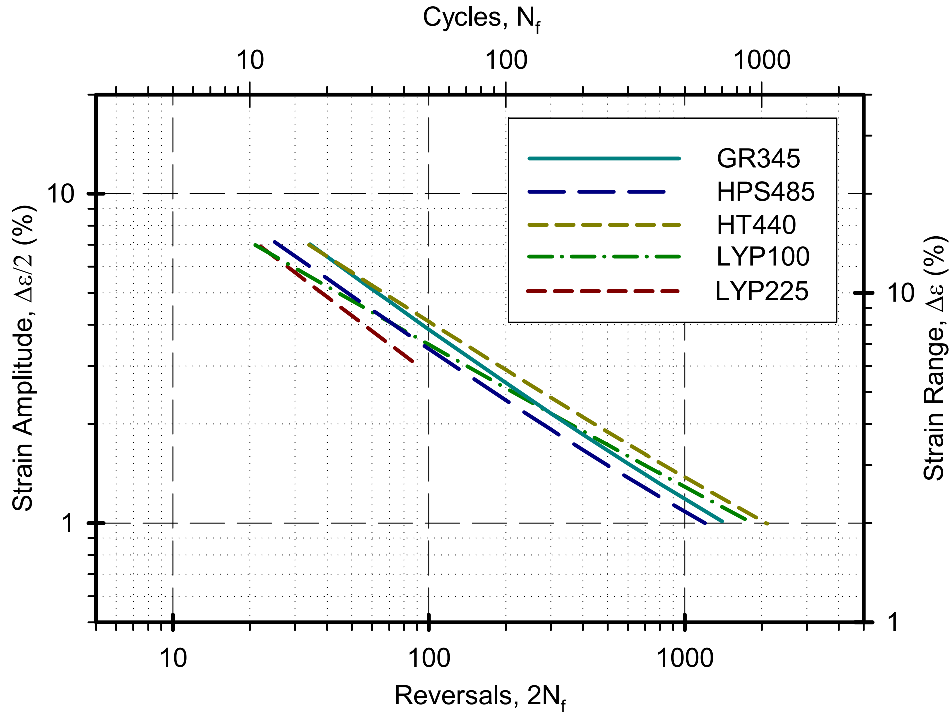


Figure 4-3: Fatigue Strain Life Comparison for All Steels

SECTION 5
LIMITATIONS OF COUPON TEST RESULTS

The coupon test results provided a strong foundation for understanding the influence of material properties on earthquake structural behavior. However, the following limitations of the stress-strain and fatigue life experiments are noted as they relate to the applicability of the coupon results to general earthquake engineering applications:

- The stress-strain and low cycle fatigue tests were conducted on the material properties of the individual steels under axial strains. Steels in structural components are often subjected to multi-axial strains for which different behavior could result.
- Typical structural components have weldments that may alter the characteristic properties of these metals and consequently the fatigue life properties. Welding introduces residual stresses, stress concentrations and material changes that can have adverse effect on the fatigue life characteristics.
- Strains induced by earthquake loading are much more irregular than the complete reverse cyclic strains used for the coupon experiments. The load history can especially affect the fatigue life.
- The fatigue results provided life estimates for a wide range of plastic strains, but the effectiveness of the fatigue life model is limited to the range of the strain amplitudes tested. As a result, the limited data available for LYP225 confines the range to a narrower band of strain amplitudes.

SECTION 6
CONCLUSIONS

Plate steels of varying grade were subjected to repeated cyclic plastic axial strains between 1% and 7% strain amplitude. The experimental results and comparisons showed the following:

- The power function relationship approximated closely the cyclic stress-strain behavior for all steel grades.
- The cyclic stress for structural grade steels stabilized to a constant within the first two cycles, but for low yield point steels the stress did not stabilize.
- The cyclic hardening, which was measured as the ratio of cyclic stress normalized to the measured yield strength, was largely dependent on the individual grades of steel. HPS485 and HT440 had the lowest cyclic hardening ratios of less than 1.5, while LYP100 had cyclic hardening ratio exceeding 4.5.
- The strain rate was found to have minimal effect on the yield and cyclic characteristics of all of the steel grades for the limited number of specimens evaluated.
- The fatigue strain-life relationship approximated closely the low cycle fatigue life for all steel grades.
- Overall, the fatigue life of all of the steels was similar within the range of strain amplitudes considered.

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University at Buffalo, The State University of New York
Red Jacket Quadrangle ▪ Buffalo, New York 14261
Phone: (716) 645-3391 ▪ Fax: (716) 645-3399
E-mail: *mceer@buffalo.edu* ▪ WWW Site *http://mceer.buffalo.edu*

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