Fatigue properties of high performance steel

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Abstract

A low carbon content, the addition of alloying elements, and improved mill practices have imparted high performance steel (HPS) with superior toughness, strength, and weldability. Its performance in fatigue, however, is not well understood. A research program presently being conducted at the University of Alberta has obtained the necessary material input parameters for fatigue life predictions. The fatigue performance of two different heats of HPS 485W steel is compared to two other grades of structural steel: A7 steel commonly found in older structures, and G40.21 350WT steel, commonly used in modern bridge structures. Stress or strain-controlled smooth specimen fatigue tests were conducted to obtain cyclic stress vs. strain curves, strain and stress amplitude vs. fatigue life curves, and energy per cycle vs. fatigue life curves, and to obtain the fatigue limit. Crack growth rate data were also obtained. The collected material data are used as a basis of comparison of high performance steel with more common grades of structural steel. HPS 485W steel shows high strength, good ductility, high fatigue limit level, and high fracture toughness. The fatigue test results indicate that HPS 485W steel has a fatigue resistance comparable to that of lower strength structural steels in the stable crack growth range. Its higher fatigue endurance limit, however, provides a distinct advantage.

1 Introduction

Compared to conventional structural grade steels, high performance steel (HPS) provides superior strength, improved weldability and high fracture toughness, as well as comparable ductility. The improved performance of HPS is achieved through lower levels of carbon, and other elements, in conjunction with advanced steel making practices.
As a result of the improved properties of HPS, it is rapidly gaining popularity for use in highway bridges, with over 175 bridges in the United States in various stages of design and construction [1]. However, utilizing the benefits of HPS with higher yield strengths (say, higher than 586 MPa) may not be possible under current design standards because the fatigue limit state is likely to control the design [2]. This is based on the assumption that fatigue performance of details made of HPS is the same as for conventional structural steels. Research to date on HPS has focused on strength design of HPS members. Little attention has been paid to its fatigue properties. The work presented in the following is part of a research project aimed at investigating methods of fatigue life prediction and their applicability to conventional details fabricated using high performance steel.

Since fatigue testing of large scale details is time consuming and expensive, analytical techniques that have been developed to predict both the crack initiation and the crack propagation stages of fatigue life are attractive alternatives to testing in investigating the fatigue resistance of high performance steel. Different approaches to fatigue life prediction are assessed by comparing predicted fatigue response to test results from specimens made of conventional structural steels. The validated approach and cyclic material properties for high performance steel can be used to predict the fatigue life of high performance steel details and to develop fatigue design curves for high performance steel.

The fatigue life prediction methods used in this investigation include stress-based, strain-based, and energy-based approaches for fatigue crack initiation and the early stage of crack propagation, and fracture mechanics for the remaining portion of the fatigue life. Stress amplitude, strain amplitude, or energy absorption is the empirical damage parameter $\Phi$ that has been proposed to correlate to the fatigue life, $N_f$. The damage parameter generally takes the form of

$$\Phi = K(N_f)^\alpha + \Phi_0 \quad (1)$$

where $\alpha<0$, $K>0$ and as $N_f \to \infty$, $\Phi \to \Phi_0$ ($\Phi_0$ is the value of the damage parameter at the fatigue limit) [3]. The coefficient $K$ and exponent $\alpha$ are evaluated from a regression analysis of experimental data.

As the material input information for fatigue life predictions are not available for high performance steel, tests were conducted to characterize its material properties. The paper provides the required basic test results and compares with those of normal structural steels. ASTM A709 Grade HPS 485W steel [4], the most commonly used grade of HPS in steel bridge projects in the United States, was used for the investigation presented in the following.

### 2 Test program

A test program was designed to compare the cyclic and monotonic properties of high performance steel with that of a lower strength structural steel. Chemical analysis, Charpy V-notch tests and tension coupon tests were used to characterize the steels used in this investigation. Standard Charpy V-notch
specimens were obtained from three HPS 485W steel plates of different thickness (6.4 mm, 19 mm and 51 mm) and heats. Half-size Charpy specimens were obtained from the 6.4 mm plate and full-size specimens were obtained from the 19 and 51 mm plates. All specimens were oriented in the rolling direction and the notch root was perpendicular to plate major surfaces. Standard tension coupons were obtained from the 6.4 mm and the 51 mm HPS plate, which were found to have the lowest and the highest toughness value among the three plate thicknesses.

Cyclic stress vs. strain properties were obtained from fully reversed (FR series), constant strain amplitude cyclic tests in a closed-loop servo-controlled universal testing machine. Flat sheet test specimens were machined from the 6.4 mm and the 51 mm HPS plates and polished in accordance with recommended procedure [5]. Specimens were fatigue tested under strain amplitudes varying from 0.1% to 0.625%. Failure was deemed to have occurred when the tensile load had dropped to 50% of its initial value. Tests that did not lead to failure of the test specimen were stopped at $10^7$ cycles, which is defined herein as a run-out. The results of the cyclic tests are used to obtain strain amplitude, stress amplitude, or energy per cycle vs. fatigue life curves.

Crack growth rate tests were conducted on the 6.4 mm HPS 485W steel to obtain the steady state crack propagation properties. Single-edged tension specimens SE(T) were used. The specimens were 50 mm wide, 300 mm high and 6 mm thick. The straight-through notch was 10 mm long and 2 mm high and was made by electrical-discharging machining (EDM). Although SE(T) specimens are not included in ASTM E647 [6], Blatt et al. [7] demonstrated that crack growth rate vs. stress intensity factor range data obtained from SE(T) correlated well with data obtained from standard compact tension C(T) specimens. Three specimens each were tested under load ratios, $R$, of −1 (fully reversed), 0, and 0.5. The load ratio was kept constant for both precracking and testing. An electronic imaging system was employed to visually monitor the crack length.

An important aspect of this research program is to provide a comparison of the performance of HPS with other structural steel grades. Tests were therefore conducted on a 6.4 mm thick ASTM A7 steel plate as a basis of comparison. Crack growth rates tests were also conducted under $R$ of 0.1 for G40.21 350WT steel [8] on six specimens of similar geometry to those for HPS 485W steel.

3 Test results

3.1 Fracture toughness properties

Test results for the Charpy V-notch specimens are presented in Figure 1. The Charpy V-notch energy vs. temperature curves shown in Figure 1(a) for half size HPS 485W (6.4 mm plate) and A7 steel impact specimens are remarkably different. Although there is no significant difference revealed in the upper and lower shelf energy between the two steels, the transition temperature, taken at half of the upper shelf energy, is significantly lower for HPS 485W than for A7 steel (−50°C for HPS 485W compared to +12°C for A7).
Fatigue Damage of Materials: Experiment and Analysis

Figure 1: Charpy V-notch energy vs. temperature.

Charpy impact tests conducted on specimens obtained from high performance steel of three different plate thicknesses (51, 19, and 6.4 mm), also corresponding to different heats of steel, are presented in Figure 1(b). There is a large difference in toughness between the different heats of high performance steel and the 6.4 mm plate seems to have the lowest toughness while the 51 mm plate has the highest toughness. A full curve for the 19 mm plate which has the intermediate toughness was not obtained. All three heats were early HPS heats produced with the thermo-mechanically controlled process (TMCP). The material test results presented in the following sections were obtained from specimens taken from the 6.4 mm plate and 51 mm plate, identified as HPS-LT and HPS-HT, respectively. The suffix represents the relative low toughness and high toughness character of the two high performance steel plates.

3.2 Tensile properties

The static tensile properties of the A7 and HPS 485W steels used in the test program are summarized in Table 1. Although the ductility of HPS 485W is not as high as that of A7 steel, it is considered to be very good with more than 23% elongation at rupture and 44% reduction in area. Both high performance steel plates satisfy ASTM A709 [4] requirement for a minimum elongation of 19% over a 50 mm gauge length.

<table>
<thead>
<tr>
<th>Material</th>
<th>Direction</th>
<th>Modulus (MPa)</th>
<th>Static Yield Strength (MPa)</th>
<th>Static Ultimate Strength (MPa)</th>
<th>Elongation (%)</th>
<th>Reduction in Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A7</td>
<td>Transverse</td>
<td>201 400</td>
<td>258</td>
<td>376</td>
<td>32</td>
<td>59</td>
</tr>
<tr>
<td>HPS-LT</td>
<td>Transverse</td>
<td>201 200</td>
<td>446</td>
<td>641</td>
<td>23</td>
<td>44</td>
</tr>
<tr>
<td>HPS-LT</td>
<td>Longitudinal</td>
<td>197 100</td>
<td>438</td>
<td>653</td>
<td>26</td>
<td>50</td>
</tr>
<tr>
<td>HPS-HT</td>
<td>Longitudinal</td>
<td>197 000</td>
<td>453</td>
<td>518</td>
<td>27</td>
<td>64</td>
</tr>
</tbody>
</table>
3.3 Fatigue crack initiation properties

A total of 41 fatigue tests on smooth specimens were conducted in the fully reversed strain controlled, FR, series and the fully reversed stress controlled fatigue limit, FL, series, for A7, HPS-LT and HPS-HT steels. The fatigue material specimens were oriented both in the longitudinal and in the transverse directions. The fatigue tests were conducted at strain ranges varying from 0.2% to 1.25% and at stress ranges varying from 480 MPa to 610 MPa.

3.3.1 FR series

3.3.1.1 Cyclic response During the initial stage of fatigue testing, the material response varied with the number of cycles but stabilized after approximately 500 cycles. Typically, a stable stress vs. strain behaviour was reached after 1% to 25% of the total fatigue life. Cyclic stress vs. strain data were collected from hysteresis loops at about half of the fatigue life to ensure that a stable condition had been reached. Figure 2(a) shows a comparison between the cyclic and the monotonic stress vs. strain curves for A7 and HPS-LT steel in the rolling direction. An illustration of the procedure used to obtain the cyclic stress vs. strain curve by joining the tips of the stabilized hysteresis loops is shown in Figure 2(b). A comparison of the monotonic and cyclic stress vs. strain properties for HPS 485W and A7 steels indicates that at small strain range, A7 steel softens whereas HPS 485W slightly hardens under cyclic conditions.

![Diagram](a) Smooth specimen results

![Diagram](b) Illustration of construction

Figure 2: Cyclic stress vs. strain curve.

A cyclic stress vs. strain relationship of the form

\[
\Delta \varepsilon / 2 = \frac{\Delta \sigma / 2}{E} + \left( \frac{\Delta \sigma / 2}{K'} \right)^{1/n'}
\]  

(2)

is fitted by a least-square regression analysis through the stress amplitude vs. plastic strain amplitude data. \(K'\) is the cyclic strength coefficient (MPa), \(n'\) is the cyclic strain-hardening exponent and \(E\) is the modulus of elasticity (MPa) obtained from tension coupon tests. The values of the material constants \(K'\) and \(n'\) are presented in Table 2.
3.3.1.2 Strain vs. life curve  The half-life hysteresis loops at various strain amplitudes were also used to obtain strain/stress/energy vs. life curves. The fatigue test data, expressed in terms of total strain amplitude ($\Delta \varepsilon / 2$) vs. number of cycles to failure ($N_f$), are presented in Figure 3 for HPS 485W steel in the longitudinal and transverse directions and for A7 steel in the transverse direction. Figure 3 indicates that the material coupon orientation has no significant effect on the strain vs. life curve. There is also no apparent difference between the fatigue resistance of two HPS steels and A7 steel.

Table 2: Cyclic material properties of HPS 485W and A7 steels.

<table>
<thead>
<tr>
<th>Material</th>
<th>Orientation</th>
<th>$K'$ (MPa)</th>
<th>$n'$</th>
<th>$\sigma_f'$ (MPa)</th>
<th>$b$</th>
<th>$\varepsilon_f'$</th>
<th>$c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A7</td>
<td>Transverse</td>
<td>1134</td>
<td>0.248</td>
<td>597</td>
<td>-0.092</td>
<td>0.196</td>
<td>-0.486</td>
</tr>
<tr>
<td>HPS-LT</td>
<td>Transverse</td>
<td>644</td>
<td>0.049</td>
<td>704</td>
<td>-0.047</td>
<td>2.828</td>
<td>-0.878</td>
</tr>
<tr>
<td>HPS-LT</td>
<td>Longitudinal</td>
<td>918</td>
<td>0.107</td>
<td>1018</td>
<td>-0.088</td>
<td>1.950</td>
<td>-0.794</td>
</tr>
<tr>
<td>HPS-HT</td>
<td>Longitudinal</td>
<td>649</td>
<td>0.071</td>
<td>776</td>
<td>-0.073</td>
<td>1.418</td>
<td>-1.020</td>
</tr>
</tbody>
</table>

Figure 3: Smooth specimen fatigue test results (strain–life curve).

The strain amplitude vs. fatigue life (strain–life) curve in Figure 3 can be expressed mathematically as:

$$\Delta \varepsilon / 2 = \frac{\sigma_f'}{E} (N_f)^b + \varepsilon_f' (N_f)^c$$  \hspace{1cm} (3)

where $\sigma_f'$ is the fatigue strength coefficient (MPa), $b$ is the fatigue strength exponent, $\varepsilon_f'$ is the fatigue ductility coefficient, and $c$ is the fatigue ductility exponent. The test run-outs, indicated by an arrow attached to the test result were excluded from the regression analysis. Table 2 presents the parameters used in eqn (3) for the steels tested in this program.

3.3.1.3 Stress vs. life curve  Plots of stabilized stress amplitude, $\Delta \sigma / 2$, obtained at half of the fatigue life of the smooth specimens, vs. fatigue life are presented in Figure 4. Although the difference between the transverse and longitudinal fatigue properties for HPS-LT is small, there is a significant difference in fatigue
life between the high performance steel specimens and the A7 steel. Although this seems to contradict the observation made in Figure 3, the significant difference observed between high performance steel and A7 steel is caused by the large difference in strength between the two steels.

The stress amplitude, $\Delta \sigma / 2$, vs. fatigue life, $N_f$, (stress-life) curves in Figure 4 may be expressed mathematically as:

$$\Delta \sigma / 2 = \sigma_f (N_f)^b$$  \hspace{1cm} (4)

The constants $\sigma_f$ and $b$, obtained from a regression analysis of the stress amplitude vs. life data, are presented in Table 2.

![Figure 4: Smooth specimen $\sigma$-N curve.](image)

### 3.3.1.4 Energy vs. life curve
Various measures of energy have been proposed as damage parameters, i.e., the total strain energy density per cycle, $\Delta W$, the plastic strain energy density per cycle, $\Delta W^p$, and the plastic plus tensile elastic strain energy density per cycle, $\Delta W^t$ [3]. The coefficient $K$, exponent $\alpha$, and constant $\Phi_0$ obtained by fitting experimental data to eqn (1) are shown in Table 3 for the various energy damage parameters. The limiting value of $\Delta W^p$ for most steels is in the range of $10^{-4}$ to $5 \times 10^{-2}$ MJ/m$^3$ with a mean of about $1.5 \times 10^{-2}$ MJ/m$^3$ [3], which represents only a very small percentage of $\Delta W^p$ and is therefore normally neglected (i.e., $\Phi_0 = 0$).

<table>
<thead>
<tr>
<th>Material</th>
<th>Direction</th>
<th>$\Delta W^p$</th>
<th>$\Delta W$</th>
<th>$\Delta W^t$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$K$</td>
<td>$\alpha$</td>
<td>$\Phi_0$</td>
</tr>
<tr>
<td>A7</td>
<td>Transverse</td>
<td>492</td>
<td>-0.618</td>
<td>396</td>
</tr>
<tr>
<td>HPS-LT</td>
<td>Transverse</td>
<td>3665</td>
<td>-0.860</td>
<td>1091</td>
</tr>
<tr>
<td>HPS-LT</td>
<td>Longitudinal</td>
<td>6084</td>
<td>-0.875</td>
<td>684</td>
</tr>
<tr>
<td>HPS-HT</td>
<td>Longitudinal</td>
<td>1276</td>
<td>-0.994</td>
<td>1603</td>
</tr>
</tbody>
</table>
3.3.2 FL series

The fatigue limit is defined as the stress amplitude level below which no fatigue failure takes place (i.e., the fatigue life is infinite). The test results obtained from the fatigue limit series (FL series) for HPS 485W steel are presented in Figure 5. The figure also includes some data from the fully reversed strain-controlled tests (FR series). These results combined, as shown in the figure, can be used to evaluate the fatigue limit. For the high performance steel HPS-LT, the fatigue limit is found to lie between 265 MPa and 321 MPa. Two run-outs and one failure at $7.4 \times 10^6$ cycles were observed at stress amplitude of 298 MPa, which indicates that the fatigue limit should be close to 300 MPa. On the other hand, the fatigue limit for HPS-HT lies below 285 MPa, with two failures at less than 1 million cycles. The fatigue limit can be reasonably estimated to be around 270 MPa, with one run-out and one specimen that failed at 4.3 million cycles near the lower grip. The difference in fatigue limit between the two HPS steels can be attributed to the difference in tensile strength between the two steels (Table 1). Fatigue research has indicated that the fatigue limit is closely related to the tensile strength level [9]. While the yield strength for the two steels are approximately the same, HPS-HT has a much lower ultimate tensile strength than HPS—LT (518 MPa vs. 647 MPa). As the tests were conducted on polished specimens, a surface roughness correction factor of 0.67 and 0.75 [10], for HPS-LT and HPS-HT, respectively, should be applied to obtain the fatigue limit of fatigue Category A details (hot rolled smooth details within 0.025 mm surface smoothness [11]). The fatigue limits for both HPS plates are approximately 200 MPa, whereas the corresponding value in the current AASHTO design specification is 82.5 MPa (165 MPa if expressed as a stress range) [11]. This indicates that high performance steel would provide a distinct advantage over conventional structural steels in the high cycle fatigue range.

![Figure 5: Smooth specimen fatigue limit test results.](image)

3.4 Fatigue crack growth rate

The crack growth rate test results in terms of the crack tip stress intensity factor range, $\Delta K$, for HPS-LT steel are presented in Figure 6 for load ratios, $R$, of -1, 0, and 0.5, together with their mean regression lines. The compressive portion of
the load cycle is included in calculating $\Delta K$ for $R = -1$. The mean regression lines are essentially parallel to each other, but for a given $\Delta K$, an increase in $R$ results in an increase in the crack growth rate. When $R$ is increased from 0 to 0.5, the growth rate increases by approximately 80%.

![Fatigue Crack Growth Rate Test Results](image)

Figure 6: Fatigue crack growth rate test results.

The results of tests on G40.21 350WT steel for $R = 0.1$ are also shown in Figure 6. A comparison between the two steels indicates that the crack growth properties of this particular HPS are slightly better than for 350WT steel. When compared with values from the literature [12], both the results from 350WT and the results from HPS-LT at $R = 0$ are well within the general scatter band for ferrite-pearlite steels. The upper bound to the test results corresponds well to the worst-case crack growth equation $\frac{da}{dN} = 6.9 \times 10^{-9} (\Delta K)^3$ for ferrite-pearlite steels [12].

The crack growth rate can be expressed in the following form:

$$\frac{da}{dN} = C(\Delta K)^n$$

(5)

where $C$ and $m$ are crack growth rate constants presented in Table 4 for HPS 485W (LT) steel and 350WT steel. Table 4 also presents the crack growth rate constants obtained using an operational definition of $\Delta K$ as $K_{\text{max}} - 0$ for compressive loading [6].

Table 4: Crack propagation properties of HPS 485W and 350WT steels.

<table>
<thead>
<tr>
<th>Material</th>
<th>Load Ratio $R = P_{\text{min}}/P_{\text{max}}$</th>
<th>C</th>
<th>m</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPS-LT</td>
<td>-1</td>
<td>2.27x10^{-10}</td>
<td>3.26</td>
<td>$\Delta K = K_{\text{max}} - K_{\text{min}}$</td>
</tr>
<tr>
<td></td>
<td>-1</td>
<td>2.18x10^{-9}</td>
<td>3.26</td>
<td>$\Delta K = K_{\text{max}} - 0$</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>3.06x10^{-9}</td>
<td>3.12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>5.48x10^{-9}</td>
<td>3.14</td>
<td></td>
</tr>
<tr>
<td>350WT</td>
<td>0.1</td>
<td>1.63x10^{-9}</td>
<td>3.52</td>
<td></td>
</tr>
</tbody>
</table>

Note: $\Delta K$ in MPa$\sqrt{m}$ and $da/dN$ in mm/cycle, based on test results for $5 \times 10^{-6} \leq da/dN \leq 10^{-3}$ mm/cycle.
4 Conclusions

An experimental program was conducted to investigate the fatigue performance of high performance steel and to compare its performance with that of conventional structural steels. Monotonic and cyclic material properties of two heats of HPS 485W steel and one heat of A7 steel were obtained from monotonic material tension tests, Charpy V-notch tests, and smooth specimen fatigue tests, to provide the input parameters for stress-based, strain-based and energy-based approaches. Crack growth rate tests were also conducted on HPS steel and G40.21 350WT steel. The following summarizes the findings to date of this ongoing research program.

1. The ductility of HPS 485W steel tested under monotonic tension is comparable to the ductility of conventional structural steel.
2. An early heat of HPS 485W steel shows similar upper shelf energy absorption to A7 steel, but has a significantly lower transition temperature.
3. Significant differences in toughness were observed between two different heats of HPS.
4. The fatigue crack initiation properties of a higher toughness HPS (HPS-HT) do not seem to be better than those of the lower toughness HPS (HPS-LT).
5. The HPS 485W steel tested provides a significantly higher fatigue limit than conventional structural steels.
6. A comparison of crack propagation properties of HPS and 350WT indicates that the HPS behaves similarly to conventional grades of structural steel, although it may be marginally superior.

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References


