Using Portable/In-Situ Stress-Strain Microprobe System to Measure Mechanical Properties of Steel Bridges During Service

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ABSTRACT

There are 590,232 federally reported bridges in the United States with 186,733 or 31.6% being defined as substandard (Better Roads, 1994). Developing new methods for inspection and evaluation of bridges has recently received considerable attention. The characterization of aging responses in structural materials entails establishing the fundamental relationships between service and environmental exposure and material properties. Service failures due to inaccurate characterization of aging responses might result in costly repair or premature component replacement. A novel portable/in-situ Stress-Strain Microprobe (SSM) system was developed to use an automated ball indentation (ABI) technique to nondestructively measure yield strength, true-stress versus true-plastic-strain curve, strength coefficient, strain-hardening-exponent, and to estimate fracture toughness. Example test results on metallic structural components and samples are given in this paper and a video demonstration will be presented at the Conference. The SSM technology will allow: (1) establishing current key mechanical properties which are needed as input for various damage prediction models as well as to re-evaluate the safety factors used for bridges, and (2) periodic monitoring of aging bridges to develop correlations between the SSM-measured mechanical properties and the damage accumulation as a function of bridge service usage.

Key Words: Ball Indentation, Bridge, Structural Integrity, Yield Strength, Flow Properties, Metals.

1. INTRODUCTION

There are 590,232 federally reported bridges in the United States with 186,733 or 31.6% being defined as substandard (Better Roads, 1994). For example, California has approximately 1500 steel girder bridges and 400 steel truss bridges on the public highway system. Of these, 769 have been identified as possessing either fatigue prone or fracture critical details. Developing new methods for inspection and evaluation of bridges has recently received considerable attention.

The characterization of aging responses in structural materials entails establishing the fundamental relationships between service and environmental exposure and material properties. Service failures due to inaccurate characterization of aging responses might result in costly repair or premature component replacement. Simulated service testing to characterize materials aging is fraught with deficiencies that stem from the inability to reproduce complex service conditions in the laboratory. Important aspects of environmental conditions encountered in service cannot be accurately simulated. The above mentioned
shortcomings could be overcome if in-situ mechanical properties can be obtained nondestructively during the service. The current mechanical properties can then be used to monitor the degradation mechanisms, and to develop the modeling and correlation capability to relate aging responses to materials’ properties and component performance.

A novel portable/in-situ Stress-Strain Microprobe (SSM) system was developed to use an automated ball indentation (ABI) technique to measure yield strength, true-stress versus true-plastic-strain curve, strength coefficient, strain-hardening-exponent, and to estimate fracture toughness. All SSM localized tests are computer-controlled and conducted in less than 2 minutes per ABI test. Example test results on metallic structural components and samples are given in this paper and a video demonstration will be presented at the Conference. Furthermore, potential applications of the SSM technology to assess the integrity of aging bridges are briefly discussed. The SSM technology will allow: (1) establishing current key mechanical properties which are needed as input for various damage prediction models as well as to re-evaluate the safety factors used for bridges, and (2) periodic monitoring of aging bridges to develop correlations between the SSM-measured mechanical properties and the damage accumulation as a function of bridge service usage.

2. PORTABLE/IN-SITU STRESS-STRAIN MICROPROBE SYSTEM AND ABI TESTING

A portable/in-situ stress-strain microprobe (SSM) system was developed recently by Advanced Technology Corporation (ATC) to test minimal material and determine several mechanical properties (e.g., yield strength, flow properties, strain-hardening exponent, strength coefficient) of metallic structures including their welds and heat-affected zones. The SSM system utilizes an automated ball indentation (ABI) technique which is nondestructive and provides a localized direct measurement of the stress-strain curve. The SSM system and test methods are based on well demonstrated and accepted physical and mathematical relationships which govern metal behavior under multi axial indentation loading. A summary of the automated ball indentation (ABI) technique is given in Ref. 2 while more details are given in Refs. 3-15. The testing head of the SSM system can be configured for ABI field and laboratory testing as well as for testing of miniature tensile test specimens. The ABI technique is based on strain-controlled multiple indentations (at a single penetration location) of a polished surface by a nonlinear-geometry indenter (tungsten carbide spherical indenters of 0.25 to 1.57-mm diameter). The indentation depth is progressively increased to a maximum user-specified limit with innovative intermediate partial unloadings. The applied indentation loads and associated penetration depths are continuously acquired during the ABI test and used to calculate the incremental stress-strain values based on elasticity and plasticity theories and few semi-empirical equations.

The microprobe system currently utilizes an electro-mechanically-driven indenter, high resolution penetration transducer and load cell, a personal computer (PC), a 16-bit data acquisition/control unit, and copyrighted ABI software. Automation of the test, where a PC and a test controller were used in innovative ways to control the test (including a real-time graphics and digital display of load-depth test data) as well as to analyze test data (including tabulated summary and macro-generated plots), made it accurate and highly reproducible. Results of ABI tests on various base metals, welds, and heat-affected-zones (HAZs), at different metallurgical conditions are presented and discussed in this paper. Excellent agreement was obtained between ABI-derived data and those from conventional ASTM methods.
Gradients in the yield strength and flow properties and correlations to the material microstructure in the weld and HAZ areas are discussed in Ref. 8. A 347 stainless steel (SS) flat specimen was also tested and the ABI results compared to its material certification. In-situ SSM configurations were used successfully to test a thick A533B reactor pressure vessel steel by a magnetic mounted SSM configuration (Fig. 1).

3. ABI DATA ANALYSIS

3.1 Yield strength determination from an ABI test

In a tensile test the uniaxial deformation is usually contained in the constant volume of the specimen's gage section. Hence, after the completion of elastic/linear loading of a metallic specimen, plastic-yielding and work-hardening commence and continue until necking occurs. In contrast, in an ABI test the elastic and plastic deformation are not distinctively separated. With increasing indentation penetration depth, an increasing volume of test material is forced to flow under multi axial compression caused by the indenter. Thus, in an ABI test both yielding and work-hardening occur simultaneously during the entire ABI test without a definite single-yield-point (because there is no constant deformation volume in an ABI test). Consequently, an accurate determination of yield strength should be based on the entire load-displacement curve of the ABI test as explained later. It should be emphasized here that an ABI test consisting of, for example, 7 loading/unloading indentation cycles (see Fig. 2-a), there will be 7 consecutive yielding processes (of new material each time the indenter has penetrated deeper into the test material) as well as 7 consecutive processes of work hardening (of both old and new material). Hence, the yield strength analysis in ABI testing should account for this simultaneous occurrence of yielding and strain-hardening of test material under ABI multi axial compression. Details of yield strength determination from ABI tests are given elsewhere 1-3.

The reason for the approximately linear relation of indentation load versus depth (Fig. 2-a) is because of the dual nonlinear processes occurring in opposite directions (i.e. the nonlinear increase of load versus depth due to the spherical geometry of the ball indenter is being offset by the power-law work-hardening behavior of the metallic test material). Hence, ABI tests do not exhibit the traditional segmented behavior (linear elastic followed by nonlinear/work-hardening) of the tensile load-displacement data.

For each ABI loading cycle the total penetration depth ($h_t$) is measured while the load is being applied, then converted to a total indentation chordal diameter ($d_t$) using the following equation:

$$d_t = 2 \left( h_t D - h_t^2 \right)^{0.5}$$

where $D$ is the indenter diameter. Data points from all loading cycles up to $d_t/D = 1.0$ are fit by linear regression analysis to the following relationship:

$$P/d_t^2 = A (d_t/D)^{m-2}$$

where $P$ is the applied indentation load, $m$ is Meyer's coefficient, and $A$ is a test material (or specimen) parameter obtained from the regression analysis of test data of $d_t/D$ versus $P/d_t^2$. The test material

$$d_t = 2 \left( h_t D - h_t^2 \right)^{0.5}$$
FIG. 1--A portable Stress-Strain Microprobe (SSM) system is, magnetic mounted on a thick steel plate, used here for in-situ testing of A533B reactor pressure vessel steel. (The bench-top system, which is not shown here, has a support platen for laboratory specimen testing.)

Parameter (A) is then used to calculate the yield strength ($\sigma_y$) of the material using the following equation:

$$\sigma_y = \beta_mA$$

(3)

where $\beta_m$ is a material-type constant (e.g., a single value of $\beta_m = 0.2285^{2,3}$ is applicable to all carbon steels whether cold rolled, hot rolled, or neutron irradiated). The value of $\beta_m$ for each class or type of material is determined from regression analysis of various tensile yield-strength values (measured from specimens with different heat treatments and flow properties and machined from different orientations) and their corresponding "A" values as measured from entire ABI curves (up to $d/D = 1.0$). In equation 3 above, the units of A and $\sigma_y$ should be the same.

3.2 Flow properties

The homogeneous plastic flow portion of the true-stress ($\sigma_t$)/true-plastic-strain ($\epsilon_p$) curve can be represented by the familiar power law equation:

$$\sigma_t = K \epsilon_p^n$$

(4)

where $n =$ strain-hardening exponent and $K =$ strength coefficient. It should be noted that this representation is not a necessary requirement for determining the indentation-derived $\sigma_t-\epsilon_p$ data as will be shown later (equations 5 and 6) but it can be used to determine the strain hardening exponent over the $\epsilon_p$...
FIG. 2--Comparison of ABI test results on base metal (BM), heat-affected-zone (HAZ), and weld metal (Weld) in a double-V weld of a high carbon steel, (a) indentation load-depth plot, (b) true-stress/true-plastic-strain data and curve fitting.
A computer program is used to solve the following equations and to thereby determine the flow curve from the ABI data.

\[
\varepsilon_p = 0.2 \frac{d_p}{D} \quad (5)
\]

\[
\sigma_t = 4P/\pi d_p^2 \delta \quad (6)
\]

where

\[
d_p = \{0.5 CD \left[ h_p^2 + (d_p/2)^2 \right] / \left[ h_p^2 + (d_p/2)^2 - h_p D \right] \}^{1/3} \quad (7)
\]

\[
C = 5.47P(1/E_1 + 1/E_2) \quad (8)
\]

\[
\delta = \begin{cases} 1.12 & \text{if } \phi \leq 1 \\ 1.12 + \tau \ln \phi & 1 < \phi \leq 27 \\ \delta_{\text{max}} & \phi > 27 \end{cases} \quad (9)
\]

\[
\phi = \varepsilon_p E_2 / 0.43 \sigma_t \quad (10)
\]

\[
\delta_{\text{max}} = 2.87 \alpha_m \quad (11)
\]

\[
\tau = (\delta_{\text{max}} - 1.12) / \ln(27) \quad (12)
\]

In the above equations, \( \sigma_t \) is the true stress, \( \varepsilon_p \) is the true-plastic-strain, \( d_p \) is the plastic indentation diameter, \( D \) is the diameter of the ball indenter, \( P \) is the applied indentation load, \( h_p \) is the plastic indentation depth, \( E_1 \) is the elastic modulus of the indenter, \( E_2 \) is the elastic modulus of the test material, \( \delta \) is a parameter whose value depends on the stage of development of the plastic zone beneath the indenter, \( \alpha_m \) is a parameter proportional to the strain rate sensitivity of the test material or specimen (e.g., for low strain-rate-sensitive materials \( \alpha_m = 1.0 \)), and "ln" is the natural logarithm.

The engineering ultimate strength (UTS) can be calculated from the ABI test results (if the material stress-strain curve follows a power law) as follows:

\[
\text{UTS} = K \cdot (n/e)^n \quad (13)
\]

### 3.3 Brinell hardness

The Brinell hardness number (HB) can also be determined from the ABI test using the maximum indentation load (\( P_{\text{max}} \) in Kgf) and the final impression diameter (\( d_f \) in mm) and the indenter diameter (\( D \) in mm) using the following equation (Standard Test Method for Brinell Hardness of Metallic Materials, ASTM E 10-84):

\[
\text{HB} = 2P_{\text{max}} / [\pi D (D^2 - d_f^2)^{0.5}] \quad (14)
\]
4. RESULTS AND DISCUSSION

4.1 In-situ ABI testing of structural components

A flat 347 stainless steel (SS) specimen obtained from an aerospace alloy (Heat No. F846) was tested prior to testing the 347 SS pipe to establish a comparison between ABI and tensile test results. The ABI-measured yield strength of 316 MPa (from one 7-cycles test) was in good agreement with the tensile yield strength of 317 MPa (indicated on this material's test report). A total of five ABI tests were then performed on the 100 mm outer diameter 347 SS pipe (5 mm thick) containing a circumferential weld (308 SS). The testing head of the portable/in-situ stress-strain microprobe system was clamped on the pipe using four 90° V-blocks. This mounting method allowed the testing head to be rotated 360° and clamped rigidly for ABI testing at any location of the weld, HAZ, or the base metal. A value of $\beta_m = 0.191$ (Ref. 2) was used for all ABI tests on stainless steel samples and pipe materials. An example of the in-situ ABI test results from the welded 347 SS pipe are summarized in Table 1 below. These ABI test results show that the flow properties measured by the microprobe at three circumferential weld areas are in good agreement with each other and are consistently slightly lower than those at the base metal and the HAZ test locations. The above in-situ tests also successfully demonstrate the potential applicability of the microprobe system to nondestructively test pressure vessels, pipes, bridges, etc.

<table>
<thead>
<tr>
<th>Test Area</th>
<th>ABI-True Stress/ True-Plastic Strain (Equation)</th>
<th>ABI-Yield Strength (MPa)</th>
<th>Ultimate Strength (MPa)</th>
<th>Brinell Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weld Metal (308 SS):</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test No. 1</td>
<td>$\sigma_t$ (MPa) = 990 $\epsilon_p^{0.198}$</td>
<td>283</td>
<td>589</td>
<td>169</td>
</tr>
<tr>
<td>Test No. 2</td>
<td>$\sigma_t$ (MPa) = 920 $\epsilon_p^{0.190}$</td>
<td>283</td>
<td>555</td>
<td>164</td>
</tr>
<tr>
<td>Test No. 3</td>
<td>$\sigma_t$ (MPa) = 971 $\epsilon_p^{0.190}$</td>
<td>300</td>
<td>586</td>
<td>172</td>
</tr>
<tr>
<td>HAZ:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test No. 4</td>
<td>$\sigma_t$ (MPa) = 1060 $\epsilon_p^{0.191}$</td>
<td>331</td>
<td>638</td>
<td>186</td>
</tr>
<tr>
<td>Base Metal (347 SS):</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test No. 5</td>
<td>$\sigma_t$ (MPa) = 1097 $\epsilon_p^{0.197}$</td>
<td>325</td>
<td>654</td>
<td>188</td>
</tr>
</tbody>
</table>

4.2 ABI testing of welds and neutron-irradiated materials

The bench-top configuration of the stress-strain microprobe was used in testing laboratory specimens of a double-V weld from a high strength steel. The ABI test results at three test locations - base metal (BM), heat-affected-zone (HAZ), and weld metal (Weld)- are shown in Fig. 2. This figure shows that the flow properties (true-stress/true-plastic-strain curve) of the HAZ is not necessarily bracketed by those from the BM and Weld on both sides of the HAZ material. It might be higher (Fig. 2) or lower than both of them (as seen in other ABI tests not in this paper). The nondestructive aspect of the ABI technique allows testing welded joints without the need to destructively machine miniature specimens which might also release residual stresses (generated from the welding procedure). Furthermore, the localized ABI
testing allows testing very narrow and/or irregular geometry HAZ areas. The SSM system can be used to map out gradients in the stress-strain behavior of welded structural components nondestructively in-situ. Hence, structural integrity and/or proper welding procedures and post-weld heat treatments can be evaluated.

The ABI technique was used to assess the degree of neutron-embrittlement damage and the percentage ductility recovery due to post-irradiation thermal annealing. To establish a reference condition, ABI tests were conducted on the end tabs of broken, flat, miniature, tensile specimens of A533B-1 pressure vessel steel. Both tensile and ABI tests were conducted using the same SSM system. Excellent agreement between stress-strain curves from both ABI and tensile tests is shown in Fig. 3. The ABI-measured stress-strain curves (Fig 4) show that the 343°C/168h thermal annealing resulted in a partial recovery while the thermal annealing at 454°C/168h resulted in full recovery of mechanical properties of the irradiated A533B [Heavy Section Steel Technology (HSST) Plate 02]. This was consistent with the results from destructive fracture toughness and Charpy impact tests. The results shown in Fig. 4 demonstrate the capability of the SSM system to quantify the degree of embrittlement and recovery due to mitigation procedures of nuclear reactor pressure vessel steels. Furthermore, the SSM system can also monitor, nondestructively in-situ, the re-embrittlement rate of nuclear pressure vessels following their thermal annealing during their life-extension. Figure 4 also demonstrates the capability of the SSM technology to (a) monitor other damage conditions such as those of bridges experiencing aging and accident conditions (e.g. earthquakes), and (b) verify the adequacy of mitigation actions, such as post-weld heat treatment procedures.

5. CONCLUSIONS

A novel portable/in-situ Stress-Strain Microprobe (SSM) system was developed to use an automated ball indentation (ABI) technique to nondestructively measure elastic modulus, yield strength, true-stress versus true-plastic-strain curve, strength coefficient, strain-hardening-exponent, and to estimate fracture toughness. The SSM technology will allow: (1) establishing current key mechanical properties which are needed as input for various damage prediction models as well as to re-evaluate the safety factors used for bridges, and (2) periodic monitoring of aging bridges to develop correlations between the SSM-measured mechanical properties and the damage accumulation as a function of bridge service usage. The applications and potentials of SSM system are summarized as below:

(1) The ABI technique of the SSM system was successful in accurately determining the yield strength and measuring the flow properties of welds in several metallic materials and structural components. The gradients in mechanical properties of weld metals and their HAZs were successfully determined from ABI tests conducted on both laboratory specimens and on structural components.

(2) The SSM system quantified the degree of neutron-embrittlement damage as well as the percentage recovery in mechanical properties resulting from post-irradiation thermal annealing of nuclear pressure vessel steels.

(3) The in-situ nondestructive capability of the SSM system can be used to monitor the aging of bridges and other critical components and to verify their structural integrity. Furthermore, welding and repair procedures can be accurately assessed.
FIG. 3--Comparison between true-stress/true-plastic-strain curves obtained from ABI and tensile tests on A533B-1 pressure vessel steel.

FIG. 4--Stress-strain curves from ABI tests on A533-B1 (HSST Plate 02) in four conditions, i.e. unirradiated, neutron-irradiated (embrittled), and two post-irradiated thermally-annealed conditions (to mitigate its radiation damage).
6. REFERENCES


