STRUCTURAL PROPERTIES OF STEELS SUBJECTED TO MULTIPLE CYCLES OF DAMAGE FOLLOWED BY HEATING REPAIR

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ABSTRACT

Experimental investigations were conducted to evaluate the effects of multiple cycles of damage followed by heating repair on the structural properties and fracture toughness of A36, A588, and A7 bridge steels. The test specimens were subjected to multiple cycles of tensile damage followed by compressive restraining stress and heat shortening repair. The damage and repair parameters considered were the damage strain (ε_d), the restraining stress (σ_r), the number of damage-repair cycles (N_r), and the maximum heating temperature (T_{max}). Seventy-five A36, A588, and A7 steel specimens were subjected to multiple damage-repair cycles with T_{max} limited to the recommended limit of 650°C. Sixteen additional A36 steel specimens were subjected to multiple damage-repair cycles with T_{max} greater than the recommended limit (T_{max}=760 or 840°C). Standard material specimens were fabricated from the damaged-repaired steel specimens and tested according to the applicable ASTM standards. The results from the standard material tests indicate that that multiple damage-repair cycles have a relatively small influence (± 15%) on the elastic modulus, yield stress, and ultimate stress, and a significant influence on the ductility (% elongation) and fracture toughness of damaged-repaired bridge steels. These effects of the multiple damage-repair cycles on the fundamental structural properties and fracture toughness of various bridge steels are summarized in the paper.

Keywords: heat treatment, steel bridges, notch toughness, stress, strain, hardness

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INTRODUCTION

The fascia beams of steel bridges are occasionally damaged by collisions with over-height trucks. The damage primarily includes out-of-plane bending and twisting of the steel fascia beam, and in several cases fracture of the diaphragm-to-beam connections, and denting, gouging, and cracking of the beam flange close to collision location. The damaged steel fascia beam can be repaired in-situ by: (a) heat straightening the out-of-plane bending and twisting, (b) refurbishing the diaphragm-to-beam connections, and (c) other procedures such as grinding, drilling holes, and providing splice plates to address the localized denting, gouging, and cracking types of damage. Heat straightening usually forms a major part of this repair, and can be performed following the procedures outlined by FHWA (Avent and Mukai 1998), NCHRP (Shanafelt and Horn 1984), or the applicable state departments of transportation (DOTs).

In some cases, the same steel fascia beam is subjected to multiple collision damages followed by heat straightening repairs over its service life. This raises concerns regarding the acceptability of the damaged-repaired steel beam due to the detrimental effects of multiple damage-heat straightening repair cycles on the steel structural properties and fracture toughness. Currently, this knowledge of the detrimental effects of multiple damage-repair cycles is lacking. A recent survey (Varma et al. 2004) indicates that most state DOTs do not have specific provisions for evaluating and replacing steel beams subjected to multiple damage-repair cycles. Some DOTs prescribe an upper limit on the number of damage-repair cycles after which the beam must be replaced, while several other DOTs rely on engineering judgment combined with other criteria such as the damage magnitude, type and age of the structure, and the number of damage-repair cycles. This survey also indicated that most state DOTs are interested in research-based guidelines for evaluating and replacing steel beams subjected to multiple damage-repair cycles.

BACKGROUND

Prior research has focused mostly on developing efficient heat straightening repair techniques and demonstrating their effective use in the field (e.g. Roeder 1986, Avent and Mukai 2001, Avent et al. 2000a, and Avent et al. 2000b). Limited research has been conducted to evaluate the effects of heat straightening on the structural properties and fracture toughness of repaired steel (e.g., Avent et al. 2000c, Avent and Fadous 1989). Avent et al. (2000c) conducted experimental investigations to determine the effects of a single damage-heat straightening repair cycle on the structural properties of A36 steel plate specimens. The plates were damaged by bending about the major axis and repaired using Vee heating patterns. The structural properties of the damaged-repaired steel were measured at the apex, middle, and bottom of the Vee heated region. The experimental results indicated that after one damage-repair cycle: (a) the elastic modulus decreases by up to 30%, (b) the yield stress increases by up to 20%, (c) the ultimate stress increases by up to 10%, and (d) the ductility (% elongation) decreases by up to 30%.

Avent et al. (2000c) also tested four A36 steel W6x9 beams by subjecting them to one, two, four, and eight damage-heat straightening repair cycles, respectively. The structural properties of the damaged-repaired steel were measured at the apex, middle, and bottom of the Vee heated regions. The experimental results indicated that multiple damage-repair cycles progressively: (a) increase the yield stress and the ultimate stress, (b) increase the ratio of yield stress to ultimate stress, (c) decrease the modulus of elasticity, and (d) reduce the ductility (% elongation) of the damaged-repaired steel. The effects of damage-repair cycles on the fracture toughness of the steel were not investigated.

Avent and Fadous (1989) conducted experimental investigations on composite beams (A36 steel W24x76 beam with concrete slab) by subjecting them to multiple damage-heat straightening repair cycles. The steel section of the composite beam cracked during the fourth damage-repair cycle, which led the researchers to recommend a limit of two damage-repair cycles for the same location in a steel beam. This recommendation is included in FHWA (Avent and Mukai 1998) and followed by some DOTs (Varma et al. 2004).

The authors have recently conducted a research project focusing on the effects of multiple damage-heat straightening repair cycles on the structural properties and fracture toughness of various bridge steels (A36, A588, and A7). The damage and repair parameters included in the study were the damage strain (ε_d), the restraining stress (σ_r), the number of damage-heat straightening repair cycles (N_r), and the maximum heating temperature (T_{max}). The research project was conducted in two phases. Phase I conducted laboratory-scale experimental investigations to evaluate the effects of these parameters on the structural properties, namely, the elastic modulus, yield stress, ultimate stress, ductility (% elongation), surface hardness, and fracture toughness of the bridge steels, and phase II conducted large-scale experimental investigations to verify the findings from phase I. This paper summarizes the results and findings from the phase I of the study. The results and findings from both phases of the study are presented in detail in the final project report by Varma and Kowalkowski (2004)

EXPERIMENTAL INVESTIGATIONS

The relevant bridge steels for this research project were identified by analyzing the Michigan high load hits database from 1976-2001 (Varma et al. 2004). This database analysis indicates that the bridge steels that are most frequently subjected to damage-heat straightening repair cycles are A7, A373, A588, and A36. Approximately 56% of the damage-heat straightening repair incidents were for A7 steel, 35% of the incidents were for A373 steel, 6% were for A588 steel, and the remaining were for A36 steel. Thus, A7 and A373 are the most frequently damaged-repaired steels and relevant for this research project. However, both of these are older construction steels that are no longer available commercially. A36 steel is the closest in chemical composition to these older A7 and A373 steels, and it is readily available. Hence, the experimental investigations focused on A36 and A588 steels. Additionally, since A7 steel is extremely relevant, one 7.3 m. long W24x76 beam made from A7 steel was acquired from a decommissioned steel bridge in Michigan and used to fabricate some specimens as explained later.

Testing Approach

Two possible approaches were considered for conducting the experimental investigations. The first approach involves fabricating steel plate specimens, damaging them in bending about the major axis, and repairing using Vee heating patterns and restraining moments (e.g., Roeder 1986, Avent et al. 2000a, Avent et al. 2000c). This approach subjects the plate cross-section (depth) and length to different magnitudes of damage strain, restraining stress, and heat straightening repair. This precludes obtaining several material specimens subjected to consistent damage and repair magnitudes and testing them to obtain statistically significant structural properties.

The second approach involves fabricating dog bone shaped steel plate specimens with reduced test-areas, damaging the test-areas in uniaxial tension, and repairing them using strip heating patterns and compressive restraining forces. This second approach does not incorporate the influence of longitudinal residual stresses that develop in a plate section after damage and repair. However, the specimen test-areas are subjected to consistent damage strains, restraining stresses, and heat straightening repair. This facilitates obtaining several material specimens from the test-areas and testing them to obtain statistically significant structural properties for the damaged-repaired steels, which is the focus of this research. Hence, this second approach was used.

Undamaged Steel Structural Properties

The structural properties of the undamaged A36, A588, and A7 steels were determined to compare with the damaged-repaired steel properties obtained later. These structural properties were determined by testing standard material specimens fabricated from the original undamaged steel plates, i.e., the original 25.4 mm. thick A36, A588, steel plates, and the 11.5 mm. thick web plate of the W24x76 A7 steel beam. The material specimens were fabricated along the same overall grain direction as the material specimens from the damaged-repaired steels. For each steel type; at least three uniaxial tension specimens were fabricated and tested according to ASTM E8 (1999a), several charpy V-notch (CVN) specimens (at least six each from quarter and mid thickness) were fabricated and tested at 4.5^oC (40^oF) according to ASTM E23 (1999b), and Rockwell hardness tests were conducted on the side of a CVN specimen closest to the plate surface according to ASTM E18 (1999c). The resulting uniaxial stress-strain (σ–ε) curves from the tension tests were used to determine the mean elastic modulus (E_o), yield stress (σ_{yo}), ultimate stress (σ_{uo}), and % elongation (e_o) values. The resulting CVN fracture toughness values were used to calculate the mean fracture toughness values for the quarter (FT_o-Q) and mid thickness (FT_o-M), respectively. Additionally, the average surfaces hardness values (H_{do}) were also calculated from the measurements. Table 1 summarizes these mean structural properties (E_o, σ_{yo}, σ_{uo}, e_o), surface hardness (H_{do}), and fracture toughness values (FT_o-Q, and FT_o-M) for the undamaged A36, A588, A7, and overheated A36 steels.

Test Specimens

Several dog-bone shaped steel plate specimens were fabricated from A36, A588, and A7 steel. Figure 1(a) shows the details of the A36 and A588 steel specimens. All the specimens of a particular steel type (A36 or A588) were made from the same 25.4 mm. nominal thickness steel plate, and the specimen lengths were parallel to the rolling direction of the original plate. The specimen dimensions (203 x 1175 mm.) were designed to concentrate yielding and damage within the test-area. The test-area dimensions (83 x 127 mm.) were designed to accommodate two standard ASTM uniaxial tension specimens and six charpy V-notch (CVN) specimens (ASTM 1999 a, b). Figure 2 (a-c) shows the dimensions and layout of these material specimens within the test area. The uniaxial tension specimens were cylindrical with a diameter of 13 mm. and gage length of 51 mm. Three CVN specimens were fabricated each from the quarter and mid-thickness of the plate.

The details of the A7 steel specimens are shown in Figure 1(b). These specimens were fabricated from the 11.5 mm. nominal thickness web of the acquired W24x76 steel beam. The W24x76 steel beam was approximately 7.3 m. long, and it was cut into three 2.3 m. long segments. The specimen dimensions (200 x 991 mm) were designed to obtain at least two rows of three specimens each (i.e., six total specimens) in the direction of rolling from each 2.3 m. long segment. The test-area dimensions (83 x 127 mm.) were identical to those for the A36 and A588 specimens, with the exception that the plate thickness was 11.5 mm. The test area accommodates two standard uniaxial tension specimens and six CVN specimens. Due to the reduced plate thickness of 11.5 mm, the uniaxial tension specimens were flat (not cylindrical) with 13 mm. width, 51 mm. gage length, and the thickness of the plate. As shown in Figure 2(d), all the CVN specimens were fabricated from the mid-thickness of the 11.5 mm. thick plate.

Test Setup

The test setup for subjecting the steel specimens to multiple damage-heat straightening repair cycles is shown in Figure 3. The primary components of the test-setup are identified in the figure. The test-setup included a bottom steel beam that was post-tensioned to the laboratory strong floor. Two hollow-core hydraulic actuators were bolted to the bottom steel beam and connected to a top beam using 63.5 mm.

diameter threaded rods and several bearing plates and nuts as shown in Figure 3. The test specimens were bolted to the bottom and top steel beam using 28.5 mm diameter high strength steel bolts. The actuators used hydraulic pressure generated by an electric pump to push up or pull down the top steel beam, thus subjecting the test specimens to tensile or compressive axial forces, respectively. The hydraulic pressures in both actuators were equalized using special split-flow and needle valves. Four concrete blocks were post-tensioned to the laboratory strong floor to restrain out-of-plane buckling of the test-setup.

Test Matrix

Several A36, A588, and A7 steel specimens were tested by subjecting them to multiple damage-heat straightening repair cycles. For each steel type, three damage strains (ε_d), two restraining stresses (σ_r), and up to five damage-heat straightening repair cycles (N_r) were considered. The damage strains were based on the strain ductility of the steel, and were limited to a maximum value of 100 times the yield strain based on the recommendations of Avent et al. (2001). Two restraining stresses (one low and one high) were considered for each damage strain value. These restraining stresses were selected to prevent yielding at ambient temperatures and buckling at elevated temperatures. For each damage strain-restraining stress combination, up to five specimens were tested by subjecting them to multiple damage-heat straightening repair cycles (one, two, three, four, or five repeated cycles). The emphasis was on steels repaired according to the current heat straightening guidelines (e.g. FHWA or NCHRP). Hence, most of these specimens were repaired with maximum heating temperatures T_{max} limited to the recommended limit of 650^{o}C. The test matrices for the A36, A588, and A7 steel specimens are presented in Tables 2, 3, and 4, respectively. The specimen nomenclature in Tables 2-4 consists of the steel type, the damage strain-to-yield strain ratio ($\varepsilon_d/\varepsilon_{yo}$), the restraining stress-to-yield stress ratio in % (σ_r/σ_{yo}), and the number of cycles of damage-heat straightening repair (N_r). As shown in Tables 2-4, twenty-eight A36, thirty A588, and seventeen A7 steel specimens were tested with T_{max} limited to 650^{o}C.

Overheating of the steel above the recommended limit of 650^{o}C occurs occasionally during heat straightening in the field (Varma and Kowalkowski 2004, Avent and Mukai 1998). Hence, experimental investigations were conducted on some A36 steel specimens to evaluate the effects of overheating on their structural properties and fracture toughness. These investigations focused on A36 steel because it is the closest in chemical composition to A7 and A373 steels, which are most relevant to this study. Table 5 summarizes the test matrix for the overheated A36 steel specimens. As shown in Table 5, sixteen A36 steel specimens were tested. Two damage strains, two restraining stresses, two numbers of damage-repair cycles (1 and 3), and two overheating temperatures (760 and 840^oC) were considered. The overheating temperatures were greater than the eutectoid phase transformation temperature (A_{c1} =727^oC) of steel, and were selected based on the following rationale.

Figure 4 shows the iron-iron carbide (Fe-Fe_3C) phase equilibrium diagram for steel along with the phase transformation temperatures (Callister 1997). The overheating temperatures for the A36 steel specimens (carbon content of approximately 0.15%) are also indicated in the Figure along with the corresponding phase transformation temperatures (A_{c1} and A_{c3}) for comparison. As shown in Figure 4, A36 steel has a ferrite-pearlite microstructure between the ambient and A_{c1} (727^oC) temperatures; it has a ferrite-austenite microstructure between the A_{c1} (727^oC) and A_{c3} (843^oC) temperatures; and it has a pure austenite phase for temperatures greater than the A_{c3} (843^oC) temperature. The first overheating temperature (760^oC) is between the A_{c1} and A_{c3} temperatures corresponding to the ferrite-austenite microstructure and the second overheating temperature (870^oC) is greater than the A_{c3} temperature corresponding to the pure austenite phase. Thus, the overheating temperatures were selected to produce the range of phases for A36 steel.

EXPERIMENTAL PROCEDURE

All the A36, A588, A7, and overheated A36 specimens were subjected to multiple damage-heat straightening repair cycles as follows:

Damage Cycles

The specimens were first damaged to achieve the target damage strain (ε_d) in the test area. The hydraulic actuators in the test-setup (see Figure 3) were used to subject the specimens to monotonically increasing (static) tensile forces. The specimens were damaged statically to maintain better control over the applied damage strain (ε_d). Impact (dynamic) damage is more realistic but difficult to control to achieve the required damage strain. The hydraulic pressures in the actuators were measured using pressure transducers (see Figure 3), and the forces applied by them were calculated by multiplying the measured pressures with the calibrated piston areas (Varma and Kowalkowski 2004). The tensile force applied to the specimen was calculated as the sum of the actuator forces. The average axial stress in the specimen test-area was calculated as the applied tensile force divided by the cross-sectional area. During the first damage cycle: (a) the axial strain at the center of the test area was measured using longitudinal strain gages, and (b) the elongation of the test-area was measured using displacement transducers and also using digital calipers (accuracy = ±0.015 mm.). The average axial strain in the test-area was calculated as the measured elongation divided by the original length, and it was validated by comparing with the axial strains measured by the strain gages. For all subsequent damage cycles, only the average axial strains were measured and used to achieve the target damage strains ε_d in the test-area.

Heat Shortening Repair Cycles

Each specimen damaged test area was repaired (shortened) by subjecting it to compressive restraining stresses (σ_r) and strip heating. The target restraining stress (σ_r) was used to compute the compressive force to be applied to the specimen. The compressive force was applied using the actuators, and was estimated using the measured hydraulic pressure and calibrated piston area (Varma and Kowalkowski 2004). This was followed by strip heating of the test-area. Strip heats were applied simultaneously to both sides of the test-area using two oxy-acetylene torches. Two torches were chosen as opposed to one torch to relate to the heat-straightening procedures used by the MDOT Statewide Bridge Crew (Varma and Kowalkowski, 2004). It is important to note that the use of only one torch may lead to slightly different results (structural properties) due to the residual stresses that develop due to temperature gradients through the thickness.

Strip heats were applied by starting from one corner of the test area, moving laterally, and then in a serpentine motion to the other end of the test area. The first heat was applied from the bottom of the test area to the top (see Figure 2). The second heat was applied from the top of the specimen to the bottom. Further strip heats were applied by judgment often by heating thinner areas first and moving up or down as required. The steel temperature was monitored using a non-contact digital temperature indicating device and was limited to 650ºC with the exception of the overheated A36 specimens, for which the temperatures were limited to 760ºC or 870ºC as required. The heated steel was allowed to cool to ambient temperature and the remaining elongation of the test area (after cooling) was measured using digital calipers. If the remaining elongation was greater than 0.13 mm, which corresponds to a strain of approximately 0.001 mm/mm, then the restraining stress (σ_r) and strip heating were re-applied.

Each damage cycle was repaired until the remaining elongation was less than 0.13 mm, and the number of heats required to achieve the repair were noted. The number of heats varied from about 3 to 20 depending on the steel type, damage strain (ε_d), restraining stress (σ_r), and maximum heating temperature (T_{max}) values. The damage and heat straightening repair cycles were repeated the required number of times (N_r) with the appropriate damage strain (ε_d), restraining stress (σ_r), and maximum heating temperature (T_{max}) values. Thus, all the specimens were subjected to multiple damage-heat straightening repair cycles with the appropriate damage and repair parameters given in the test matrices (Tables 2-5).

Material Specimens and Testing

Standard material specimens were fabricated from the test-area of each specimen after subjecting it to the required number of damage-repair cycles. Two uniaxial tension specimens and six CVN specimens (three each from quarter and mid thickness) were obtained from the test-area of each specimen as discussed earlier (see Figure 2). The uniaxial tension specimens were tested according to ASTM E8 (ASTM 1999a), and the resulting uniaxial stress-strain (σ–ε) curves were used to determine the mean elastic modulus (E), yield stress (σ_y), ultimate stress (σ_u), and % elongation (e) values for the damaged-repaired steels. The CVN specimens were tested according to ASTM E23 (ASTM 1999b) at 4.5ºC (40^{o}F) using a verified impact testing machine. The resulting fracture toughness values were used to calculate the mean fracture toughness values for the quarter and mid thickness (*FT-Q and FT-M*). Rockwell hardness tests were also conducted on the surface of CVN Specimen 2 (identified in Figure 2) to determine the surface hardness of the damaged-repaired steel. The reported surface hardness values may be skewed due to the machining process used to fabricate the charpy specimens. However, the undamaged surface hardness tests were also conducted on similar CVN specimens with the same machining process. Hence, the hardness test results are comparative.

EXPERIMENTAL BEHAVIOR

The behavior of the specimens subjected to multiple damage-heat straightening cycles was monitored to gain additional insight into the heat straightening repair process. The average axial stress-strain (σ–ε) responses of the test-area of specimen A36-60-50-3 for three damage cycles are shown in Figure 5. As shown in Figure 5, the average axial σ–ε response for the first damage cycle compares favorably with the uniaxial σ–ε behavior of the undamaged A36 steel. For the subsequent damage cycles, the average axial σ–ε response differs slightly from the uniaxial σ–ε behavior of the undamaged steel. These differences relate to the magnitude of the yield stress and the onset of strain hardening. The apparent variation in the elastic modulus was primarily due to the lack of accuracy of the displacement transducer measurements in the elastic range. The behavior of all other specimens subjected to damage cycles was comparable to that shown in Figure 5 for specimen A36-60-50-3.

The specimen behavior during the heat straightening repair cycles was monitored by measuring the time variation of the applied restraining stress (σ_r), the steel surface temperature (T), and the axial deformation (δ) of the complete specimen length. The axial deformation of the test-area could not be measured because it was too hot to attach displacement transducers. Figure 6 shows the behavior of specimen A36-60-50-3 during the second heat straightening repair cycle. This repair cycle consisted of only three strip heats (compared to as many as 20 for other specimens), and is shown here to explain behavior clearly. The figure includes the measured time variation of σ_r, T, and δ. As shown in Figure 6, the test-area is subjected to σ_r, which is followed by strip heating. The heating causes expansion of the steel in the test-area, which increases the hydraulic pressure in the actuators and the applied σ_r slightly.

The test-area yields because the yield stress of steel at elevated temperatures (650^{o}C) is less than the applied σ_r (equal to 0.50σ_y) (Avent et al. 2000 c). This yielding causes inelastic (permanent) shortening of the specimen due to the applied compressive σ_r. The specimen shortening decreases the hydraulic pressure in the actuators and reduces the applied σ_r significantly. The specimen continues shortening (due to thermal contraction) and the applied σ_r continues decreasing as the specimen cools to ambient temperature. The remaining elongation of the test area after cooling to ambient temperature was measured using digital calipers. The restraining stress followed by strip heating was re-applied (three times as shown in Figure 6) until the test area was repaired with acceptable tolerance (defined earlier). The behavior of all other specimens during the heat straightening repair cycles was similar to the behavior of A36-60-50-3 shown in Figure 6.

The surface time-temperature (*T*-*t*) responses of the overheated A36 steel specimens were measured using a non-contact infrared thermocouple (accurate up to 1300^{o}C) to evaluate the possibility of forming brittle microstructures, e.g., martensite or bainite, instead of ferrite-pearlite upon cooling. Figure 7 shows the typical post-peak *T*-*t* cooling path for the A36 steel specimens tested in the laboratory. It includes the continuous cooling transformation (CCT) diagram for 0.13% carbon steel (ASM 1977), and the measured *T*-*t* cooling path for an A36 steel specimen that was heated and cooled outside on a cold and windy day in Michigan (temperature=1.1^{o}C or 34^{o}F). Figure 7 indicates that the cooling paths are similar for A36 specimens heated (and cooled) inside or outside the laboratory. The measured cooling paths negate the possibility of formation of brittle martensite or bainite microstructures. Thus, overheating the 25.4 mm. thick A36 steel plate does not result in the formation of brittle microstructures.

EXPERIMENTAL RESULTS

Structural Properties (E, σ_y, σ_u, and H_d) of Damaged-Repaired Steels

Tables 2 – 5 include the ratios of the damaged-repaired steel structural properties (E, σ_y, σ_u, and H_d) with respect to the corresponding undamaged steel structural properties (E_o, σ_{yo}, σ_{uo}, H_{do}) for the A36, A588, A7, and overheated A36 steels presented in Table 1. The ratios in Table 2 indicate that damage-repair cycles increase the yield stress of A36 steel slightly. σ_y varies between 104-124% of σ_{yo} with most values between 105-112% of σ_{yo}. The increase in yield stress is higher for specimens subjected to smaller ε_d, but no further trends are observed with σ_r or N_r. Damage-repair cycles do not have a significant influence on the elastic modulus, ultimate stress, and surface hardness of A36 steel. E varies between 95-110% of E_o and the variation does not have clear trends with ε_d, σ_r, and N_r. σ_u varies between 95-110% of σ_{uo}. Specimens subjected to lower ε_d have higher σ_u, but no further trends are observed with σ_r and N_r. H_d varies between 98-116% of H_{do}. Specimens subjected to lower ε_d also have higher H_d, but no further trends are observed with σ_r, or N_r.

The ratios in Table 3 indicate that damage-repair cycles have a small influence on the yield stress of A588 steel. σ_y varies between 96-111% of σ_{yo}, but the variation does not have clear trends with ε_d, σ_r, or N_r. Damage-repair cycles increase the elastic modulus of A588 steel slightly, which is unique and not observed for other steel types. E varies between 104-110% of E_o and the variation does not have clear trends with ε_d, σ_r, or N_r. σ_u varies between 94-104% of σ_{uo}. Specimens subjected to larger ε_d have slightly lower σ_u, and increasing σ_r (for the same ε_d) increases σ_u slightly. H_d varies between 99-108% of H_{do}. Specimens subjected to larger ε_d have slightly higher H_d, and increasing σ_r (for same ε_d) increases H_d.

The ratios in Table 4 indicate that damage-repair cycles have a small influence on the yield stress of A7 steel. σ_y varies between 86-121% of σ_{yo} with most values between 92-110% of σ_{yo}. The change in σ_y does not have clear trends with ε_d, σ_r, or N_r. Damage-repair cycles usually reduce the elastic modulus slightly (E varies between 85-101% of E_o). As noted in Table 4, the elastic modulus could not be measured accurately for some specimens. This was due to the initial curvature in the tension coupons from the damage-repair process. σ_u varies between 95-103% of σ_{uo}, and H_d varies between 102-114% of H_{do}. The variations in σ_u and H_d do not have clear trends with ε_d, σ_r, and N_r.

The ratios in Table 5 indicate that damage-repair cycles increase the yield stress of the overheated A36 steel. σ_y varies between 114-127% of σ_{yo}, E varies between 96-104% of E_o, and σ_u varies between 101-108% of σ_{uo}. The variations in σ_y, E, and σ_u do not have major trends with ε_d, σ_r, or N_r. Damage-repair cycles decrease the surface hardness of the overheated A36 steel slightly, which is unique and not observed for other steel types. H_d varies between 94-102% of H_{do}, but the variation does not have clear trends with ε_d, σ_r, or N_r.. Thus, the ratios in Tables 2-5 indicate that damage-repair cycles do not have a significant influence on the yield stress, elastic modulus, ultimate stress, or surface hardness of the steels. Most of these damaged-repaired structural properties (noted above) are within ± 15% of the corresponding undamaged values. The changes in the structural properties do not have major trends with the damage and repair parameters.

Ductility (% Elongation) of Damaged-Repaired Steels

Tables 2-5 include the ratios of the ductility (% elongation e) of damage-repaired steels to the ductility (% elongation e_o) of undamaged steels. The e/e_o ratios in Table 2 indicate that damage-repair cycles reduce the ductility of A36 steel significantly. The % elongation (e) values vary from 67-96% of e_o. The reduction in ductility is greater for specimens subjected to smaller ε_d (equal to $30\varepsilon_y$), but it does not have further trends with σ_r or N_r. Specimens with greater increase in ultimate stress (σ_u) have greater reduction in ductility (e). The e/e_o ratios in Table 3 indicate that damage-repair cycles reduce the ductility (% elongation) of A588 steel slightly. The % elongation (e) values vary from 74-92% of e_o with most values between 80-90% of e_o, which is quite reasonable.

The e/e_o ratios in Table 4 indicate that damage-repair cycles reduce the ductility of A7 steel significantly. The % elongation (e) values for the specimens vary between 57-89% of e_o. The specimens subjected to five damage-repair cycles (A7-30-25-5, A7-60-25-5, and A7-60-40-5) have % elongation (e) values as low as 57-60% of e_o. As seen in Table 4, increasing ε_d, σ_r, *or* N_r reduces ductility significantly, and N_r is the parameter having most influence on the ductility of damaged-repaired A7 steel. The e/e_o ratios in Table 5 indicate that damage-repair cycles reduce the ductility (% elongation) of overheated A36 steel. The % elongation (e) values vary from 72-93% of e_o, and compare favorably with the % elongation (e) values for A36 steel heated to 650^{o}C (see Table 2). The change in ductility does not have clear trends with ε_d, σ_r, or N_r, but using higher temperatures (870^{o}C or 1600^{o}F) results in greater variability.

Fracture Toughness (FT) of Damaged-Repaired Steels

Table 6 reports the fracture toughness values measured for the six CVN specimens from each damaged-repaired A36 steel specimen, and the corresponding mean quarter (*FT-Q*) and mid (*FT-M*) thickness fracture toughness values. It also includes the ratios of the mean fracture toughness values for the damaged-repaired and undamaged A36 steel ($FT\text{-}Q/FT_o\text{-}Q$ and $FT\text{-}M/FT_o\text{-}M$), which represent the normalized fracture toughness values for the damaged-repaired specimens.

The AASHTO (2004) requirement for minimum fracture toughness of bridge steels in Zone 2 (applicable to Michigan and several other states) is equal to 20 J at 4.5^{o}C (40^{o}F) for non-fracture-critical members. As shown in Table 1, the mean fracture toughness of the undamaged A36 steel was equal to 182 J, which is significantly higher than the AASHTO requirements. The mean fracture toughness value for the second (overheated) undamaged A36 steel plate was equal to 73 J at 4.5^{o}C (see Table 1), which is also higher than the AASHTO requirement, but much lower than the mean fracture toughness for the first A36 steel plate. This identifies the significant variation in mean fracture toughness values for bridge steels manufactured currently.

A manufacturer typically guarantees that the steel fracture toughness will be greater than the AASHTO requirements (lower bound), but there is no upper bound value or expected range for the fracture toughness values. This leads to the significant variation in the fracture toughness values for steels produced currently. Due to this significant variation, it is important to normalize the mean fracture toughness values (*FT-Q* and *FT-M*) for the damaged-repaired steels with respect to the mean fracture toughness values ($FT_o\text{-}Q$ and $FT_o\text{-}M$) of the undamaged steels. This normalization removes the bias caused by the fracture toughness of the undamaged steel, which can be highly variable. Hence, the fracture toughness results were evaluated by considering the normalized fracture toughness values (ratios $FT\text{-}Q/FT_o\text{-}Q$ and $FT\text{-}M/FT_o\text{-}M$) along with the measured fracture toughness values for the damaged-repaired steels.

A36 Steel

In Table 6, the fracture toughness values lower than the AASHTO requirements of 20 J at 4.5^{o}C (for non-fracture critical members) are highlighted in bold. Figure 8(a) presents the variation of the normalized fracture toughness values (ratios $FT\text{-}Q/FT_o\text{-}Q$ and $FT\text{-}M/FT_o\text{-}M$) with respect to the parameters ε_d, σ_r, and N_r. The values in Table 6 and the graphs in Figure 8(a) indicate that damage-repair cycles reduce the fracture toughness of A36 steel significantly, but the reduced fracture toughness falls below the AASHTO requirements only in a few cases. This may be due to the high fracture toughness (182 J) of the undamaged A36 steel plate. The graphs in Figure 8(a) indicate that for the A36-30 specimens (ε_d=30ε_y), the normalized quarter and mid thickness fracture toughness values agree reasonably. The normalized fracture toughness reduces to about 25% after two damage-repair cycles. It increases after two cycles, and reaches approximately 55% after four cycles. After five damage-repair cycles, the normalized fracture toughness again reduces to about 25%. Increasing the restraining stress does not seem to have a significant influence on the normalized fracture toughness.

For the A36-60 specimens, the values in Table 6 indicate that the measured fracture toughness reduces below the AASHTO requirement (20 J) after five damage-repair cycles. The graphs in Figure 8(a) indicate significant variation between the normalized quarter and mid-thickness fracture toughness values for these specimens. The normalized quarter thickness fracture toughness is typically higher than the normalized mid thickness fracture toughness. However, they both reduce below 50% after three damage-repair cycles. Increasing the restraining stress does not seem to have a significant influence on the normalized fracture toughness.

For the A36-90 specimens, the measured fracture toughness reduces below the AASHTO requirement (20 J) after five damage-repair cycles for specimens repaired with σ_r=0.25σ_y, and after three damage-repair cycles for specimens repaired with σ_r=0.50σ_y. Increasing the restraining stress seems to have a detrimental effect on toughness. The curves in Figure 8(a) indicate significant variation between the normalized quarter and mid thickness fracture toughness. For these specimens, the normalized quarter thickness fracture toughness is typically lower than the normalized mid thickness fracture toughness. In several cases, the normalized fracture toughness values are greater than 100%, which is unusual. The normalized fracture toughness of the A36-90-50 specimens (σ_r=0.50σ_y) reduces to about 25% after three damage-repair cycles.

A588 Steel

Table 7 reports the fracture toughness values measured for the six CVN specimens from each damaged-repaired A588 steel specimen, and the corresponding mean quarter (*FT-Q*) and mid (*FT-M*) thickness fracture toughness values. It also includes the ratios of the mean fracture toughness values for the damaged-repaired and undamaged A588 steel ($FT\text{-}Q/FT_o\text{-}Q$ and $FT\text{-}M/FT_o\text{-}M$), which represent the normalized fracture toughness values for the damaged-repaired specimens. Figure 8(b) shows the variation of the normalized fracture toughness (ratios $FT\text{-}Q/FT_o\text{-}Q$ and $FT\text{-}M/FT_o\text{-}M$) with respect to the parameters ε_d, σ_r, and N_r.

The values in Table 7 indicate that the measured fracture toughness never reduces below the AASTHTO requirements (20 J), which is remarkable. This may be partially due to the high fracture toughness (141 and 107 J for quarter and mid thickness) of the undamaged A588 steel. The ratios in Table 7 and the graphs in Figure 8(b) indicate that the damage-repair cycles have a significant influence on the normalized fracture toughness of A588 steel, but it rarely reduces below 50%. In several cases, the normalized fracture toughness is greater than 100%, which is remarkable. There is significant variation between the normalized quarter and mid thickness fracture toughness values, and the normalized quarter thickness fracture toughness is typically higher.

The A588-20 specimens subjected to the smaller damage strain have lower normalized fracture toughness than the specimens subjected to larger damage strains (A588-40 and A588-60). Increasing the restraining stress from 0.25 to 0.50σ_y reduces the normalized fracture toughness significantly for all the A588-20, A588-40, and A588-60 specimens. The number of damage-repair cycles N_r does not appear to have a clear trend with the changes in normalized fracture toughness.

A7 Steel

Table 8 reports the fracture toughness values for the six CVN specimens from each damaged-repaired A7 steel specimen, and the corresponding mean mid-thickness (*FT-M*) fracture toughness. It also includes the ratios of the mean fracture toughness of the damaged-repaired and undamaged A7 steel ($FT\text{-}M/FT_o\text{-}M$), which represent the normalized fracture toughness values for the damaged-repaired specimens. Figure 8(c) shows the variation of the normalized fracture toughness ($FT\text{-}M/FT_o\text{-}M$) with respect to the parameters ε_d, σ_r, and N_r. In Table 8, the fracture toughness values lower than the AASHTO requirements of 20 J at 4.5°C (for non-fracture critical members) are highlighted in bold.

The values in Table 8 indicate that the measured fracture toughness reduce below the AASTHTO requirement for some A7 steel specimens. This may be partially due to the lower fracture toughness (53 J) of the undamaged A7 steel. This highlights the importance of considering both the normalized and the raw fracture toughness values when evaluating the results. The ratios in Table 7 and the graphs in Figure 8c) indicate that the damage-repair cycles have a significant influence on the normalized fracture toughness of A7 steel specimens. They typically reduce, but in some cases increase the normalized fracture toughness of A7 steel specimens. For the A7-30 specimens, increasing the number of damage-repair cycles reduces the normalized fracture toughness. The normalized fracture toughness reduces to approximately 50% and 40% after three and five damage-repair cycles, respectively. Increasing the restraining stress from 0.25 to 0.40 σ_y seems to improve the normalized fracture toughness, but a closer inspection of the data in Table 8 for A7-30-40 specimens indicates significant variability in the fracture toughness values with several values lower than the AASHTO requirements (20 J).

For the A7-60 specimens, the normalized fracture toughness for the specimens repaired with $\sigma_r=0.25\sigma_y$ is greater than 100% after three and five damage-repair cycles, which is remarkable. This trend is further confirmed by the consistency in the fracture toughness values for the replicate specimens A7-60-25-3-1 and A7-60-25-3-2 in Table 8. Increasing the restraining stress from $0.25\sigma_y$ to $0.40\sigma_y$ reduces the fracture toughness of the A7-60 specimens significantly. The normalized fracture toughness of the

A7-60-40 specimens reduces to approximately 50% and 25% after three and five damage-repair cycles. The fracture toughness data in Table 8 indicates several values below the AASHTO requirements for A7-60-40-3 and A7-60-40-5 specimens. For the A7-90 specimens subjected to the largest damage strain, the normalized fracture toughness values remain close to 100% after one or three damage-repair cycles. This trend is further confirmed by the fracture toughness values in Table 8.

Overheated A36 Steel

Table 9 reports the fracture toughness values measured for the six CVN specimens from each damaged-repaired overheated A36 steel specimen, and the corresponding mean quarter (*FT-Q*) and mid (*FT-M*) thickness fracture toughness values. It also includes the ratios of the mean fracture toughness values for the damaged-repaired and the undamaged A36 steel ($FT\text{-}Q/FT_o\text{-}Q$ and $FT\text{-}M/FT_o\text{-}M$), which represent the normalized fracture toughness values for the damaged-repaired specimens. The values in Table 9 indicate that the measured fracture toughness values never reduce below the AASHTO requirements (20 J) and are generally much greater than the undamaged fracture toughness (78 J), which is remarkable.

The normalized fracture toughness values for the A36 specimens repaired with T_{max}=760°C (1400°F) is about 172-471%. Similarly, the normalized fracture toughness values for the A36 specimens repaired with T_{max}=870°C (1600°F) is about 111-460%. The measured fracture toughness values have significant scatter in some cases. Typically, the mid thickness fracture toughness values have more scatter than the quarter thickness toughness values. The normalized fracture toughness values for both overheated temperature do not appear to have clear trends with respect to ε_d, σ_r, or N_r. The A36 specimens repaired with T_{max} = 870°C have slightly lower fracture toughness and more scatter than the specimens repaired with T_{max} = 760°C. The surfaces of the A36 specimens repaired with T_{max} = 870°C have some surface pitting and it was more difficult to control the heating repair operation.

ASSUMPTIONS AND LIMITATIONS

The experimental investigations involved the following assumptions. The damage forces were applied statically not dynamically or by impact. The specimen test-areas were subjected to multiple cycles of tensile damage followed by heat shortening repair. This was done to subject the material to consistent damage strain, restraining stress, and heating repair, which facilitates obtaining several samples from the test-areas and testing them to obtain statistically significant results for structural properties (the focus of this research). The specimen test-area emulates the damage and repair history of the extreme tension fiber of a steel beam or plate subjected to impact damage followed heat straightening repair. However, it does not consider the effects of residual stresses or strain that may develop in the steel beam or plate. Due to these assumptions, the results and conclusions presented in this paper must be considered carefully before any action. The second phase of this research conducted large-scale experimental investigations of the effects of multiple damage-repair cycles on the structural properties and fracture toughness of W24x76 beams made from A36, A588, and A7 steels. It was designed to verify the findings from the laboratory-scale investigations presented in this paper. The results and findings of the second phase are presented in Varma and Kowalkowski (2004) and in a separate paper (Kowalkowski and Varma 2006).

SUMMARY AND CONCLUSIONS

The effects of multiple damage-heat shortening repair cycles on the structural properties and fracture toughness of bridge steels (A36, A588, and A7) were investigated experimentally. The parameters considered in the study were the damage strain (ε_d), the restraining stress (σ_r), the number of multiple damage-repair cycles (N_r), and the maximum heating temperature (T_{max}). Twenty-eight A36, thirty A588, and seventeen A7 steel specimens were subjected to multiple damage-heating repair cycles with T_{max}=650°C. Additionally, sixteen A36 steel specimens were subjected to multiple damage-repair cycles with T_{max} equal to 760 or 870°C. Two uniaxial tension and six CVN specimens were fabricated from the test-area of each damaged-repaired specimen, and tested according to the applicable ASTM standards. The material test results were used to determine the structural properties (elastic modulus E, yield stress

σ_y, ultimate stress σ_u, % elongation e, and surface hardness H_d) and the fracture toughness for the damaged-repaired steel specimens.

The structural properties for the damaged-repaired steel specimens were compared to the corresponding undamaged steel structural properties. The normalized structural properties (ratios of E/E_o, σ_y/σ_{yo}, σ_u/σ_{uo}, e/e_o, and H_d/H_{do}) for the A36, A588, A7, and overheated A36 steel specimens were reported in Tables 2-5. The fracture toughness values for the six CVN specimens for each damaged-repaired steel specimen were reported in Tables 6-9. The mean fracture toughness values for the damaged-repaired steel specimens were normalized with respect to the mean toughness values for the corresponding undamaged steel. This was done to remove any bias caused by the undamaged steel fracture toughness, which can have significant variability because of no established upper bound or range. However, both the normalized and measured fracture toughness values were used to evaluate the results.

The material test results summarized in Tables 2-5 indicate that the damage-repair cycles do not have a significant influence on the elastic modulus, yield stress, ultimate stress, and surface hardness of the A36, A588, A7 and overheated A36 steels. Most of these structural properties were within ±15% of the undamaged values. Further results regarding the ductility and fracture toughness are as follows:

A36 steel. The normalized ductility (e/e_o) of damaged-repaired A36 steel is low (66-95%). The normalized fracture toughness of damaged-repaired A36 steel is also quite low in some cases. However, the measured fracture toughness values were rarely lower than the AASHTO requirement (20J at 4.5^oC) because the undamaged steel fracture toughness was quite high (182 J). The reduction in ductility and normalized fracture toughness was greater for specimens subjected to smaller damage strain. Typically, after three damage-repair cycles, the normalized fracture toughness reduces close to or below 50%.

A588 steel. The normalized ductility (e/e_o) ductility of damaged-repaired A588 steel is quite reasonable (about 80-90%). The normalized fracture toughness of damaged-repaired A588 steel is rarely below 50% and is greater than 100% in several cases, which is remarkable. The fracture toughness values are never below the AASHTO requirement (20 J), which may be partially due to the high undamaged toughness

(102 J). The normalized fracture toughness is lower for the specimens subjected to the smaller damage strain, and decreases further with increases in restraining stress.

A7 steel. The normalized ductility (e/e_o) of damaged-repaired A7 steel is usually about 80-90%. However, after five damage-repair cycles, the normalized ductility is very low (57-64%). The normalized fracture toughness is quite low for specimens subjected to small damage strains. It reduces to about 50% after three damage-repair cycles, and decreases further with the number of cycles. Increasing the restraining stress reduces the normalized fracture toughness significantly. A7 steel specimens repaired with higher restraining stress (σ_r=0.40σ_y) have several fracture toughness values lower than the AASHTO requirement (20 J) after three or five damage-repair cycles.

Overheated A36 steel. The normalized ductility of overheated A36 steel is comparable to the normalized ductility of A36 steel specimens with T_{max}=650^{o}C. The measured fracture toughness values never reduce below the AASHTO requirements (20 J) and are generally much greater than the undamaged fracture toughness (78 J), which is remarkable. The measured fracture toughness values have significant scatter in some cases, and no clear trends with the parameters. The surfaces of the A36 specimens repaired with T_{max} = 870^{o}C have some surface pitting and more difficult to control during heating repair.

NOTATION

The following symbols are used in this paper.

A_{c1} = lower eutectoid phase transformation for steel

A_{c3} = higher phase transformation for steel

E = elastic modulus of steel

E_o = elastic modulus of steel

FT = fracture toughness of steel

FT_o = mean fracture toughness of undamaged steel

N_r = number of damage-repair cycles

T_{max} = maximum heating temperature during repair

e = percent elongation of steel

e = percent elongation of undamaged steel

δ = deflection in test area

ε_d = damage strain in the test area of specimens

ε_{yo} = yield strain of undamaged steel

σ_r = restraining stress in the test area of specimens during repair

σ_u = ultimate stress of steel

σ_{uo} = ultimate stress of undamaged steel

σ_y = yield stress of steel

σ_{yo} = yield stress of undamaged steel

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