Campus Road Bridge Heat Straightening Repair - Grundy County

The Engineering Practice for Design of Heat Straightening Repairs

Douglas C. Brunot, P.E., S.E., AWS D1.1 Certified Structural Welder
Regional Structural Manager – General Manager, Joliet Office

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References

- AASHTO/AWS D1.5 2010 Bridge Welding Code
- AWS D1.7 Guide for Strengthening and Repairing Structures
- FHWA-1F-08-999 Guide for Heat Straightening of Damaged Steel Bridge Members
- Engineering Journal/First Quarter/2001 “What You Should Know About Heat Straightening Repair of Damaged Steel”
- Avent et al. (1991), Avent and Mukai (1998)
- Ciesicki and Bulter (1968)
- Holt (1955, 1965, 1971, 1977)

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Introduction to Heat Straightening

- https://youtu.be/twWMroRvqAY
- Heat straightening has been practiced by artisans in the past rather than an exact science
- Material properties may be compromised
  - Over jacking that causes strain hardening
  - Overheating that changes the internal structure of steel
- Engineering applications have been limited due to lak of an established method
- The purpose of this presentation is to show how established engineering standards have been used for a recent repair project

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Definition of Heat Straightening

Heat-straightening is a repair procedure in which a limited amount of heat is applied in specific patterns to the plastically deformed regions of damaged steel in repetitive heating and cooling cycles to produce a gradual straightening of the material.

- Internal restraint
- External restraint
- Upsetting during heating phase
- In-plane contraction during the cooling phase
- Maximum heat does not exceed lower limit of critical temperature for carbon steel or the temper limit for tempered and quench tempered steels

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Heat Straightening Physics

- Steel is an elastic material, when deformed beyond its elastic limit is permanently deformed
- When steel is heated to high temperature, its yield strength is significantly reduced at the higher temperature

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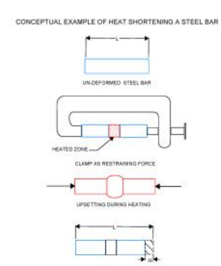
Heat Straightening Physics

- The bar is clamped, fixing both ends from translation (external restraint)
- The bar tris to expand as it is heated
- The external restraint prevents expansion
- The bar is forced to expand laterally in the heated zone
- The bar bulges in the middle and this area has a greatly reduced yield strength, resulting in plastic deformation
- As the material cools, the bulge shrinks and the bar contracts to a shorter length



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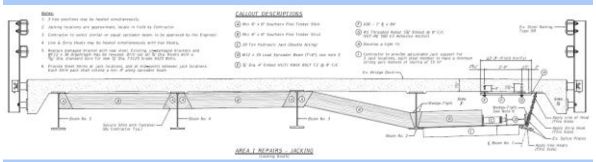
Campus Road External Restraint



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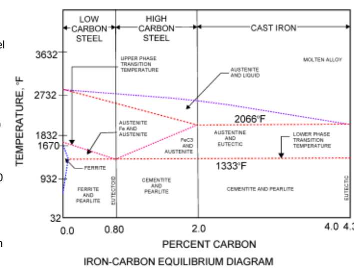
- Importance of controlling heated steel temperature
- Orifice size
- Torch speed
- Member thickness
- Carbon and low-alloy steel
  - Ferrite grains
  - Pearlite grains
- High-carbon or Pearlite steel
- Low carbon steel, softer and more like iron (ferrite)
- High carbon steel produces a harder more brittle material
- Temperatures above 1340 deg. F produce a phase change in steel (lower phase transition)
- Steel cooling from lower phase transition will return to its original crystal structure

Limits on Temperature and Jacking Force



IRON-CARBON EQUILIBRIUM DIAGRAM

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Limits on Temperature and Jacking Force

- Over jacking can cause strain hardening and sudden fracture
- Jacking stresses should be designed to approach a reduced yield strength of the steel. Campus Road design used ¼ F_y
- Jacking stresses are added to residual stress. Common practice is to limit jacking force to $0.50F_y$ of the material being straightened
- $0.50F_y$ corresponds to a mild steel heated to 1200ºF
- Jacks must be calibrated and jacking forces must be computed based on the detail resisting the jacking force

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Cooling Process During Straightening

- For best results, steel should be allowed to cool to ambient temperature before applying the next heat cycle
- Steel should be cooled to 200ºF maximum before applying the next heat cycle or it will interfere with the next heating pattern
- Natural cooling is preferred however air convection and water may be used to speed the process.
- The steel should cool to 600ºF before using artificial cooling aids
- Cooling rates that exceed 500ºF/hour may cause unwanted distortion

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Heat Application Methods

- The rate of heating should be controlled. Campus Road Bridge limit was 800ºF/hour to avoid unwanted distortion
- Use of an oxygen fuel mixture such as acetylene, propane or natural gas may be used. Acetylene is most effective as it produces high-heat quickly

Table A2. Recommended torch tips for various material thicknesses

Steel Thickness (in)	Orifice Type	Size
< ¼	Single	3
3/8	Single	4
½	Single	5
5/8	Single	7
¾	Single	8
1	Single Rosebud	8 3
2	Single Rosebud	8 3
3	Rosebud	5
>4	Rosebud	5

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Heat Application Types

- Several types of "heats" or heat application types are used
- The VEE heat is used to straighten strong axis bends in steel elements
- The heat starts at the apex of the VEE and continues in a serpentine pattern once the steel at the apex reaches 1200ºF

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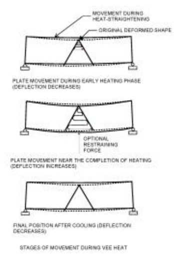
VEE Heat Pattern

- The plate will initially move upward as a result of longitudinal expansion of material above the neutral axis, producing negative bending
- The cool material adjacent to the heated area resists the normal material expansion in the longitudinal direction
- As a result the heated material will expand (upset) through the plate thickness, resulting in plastic flow
- Once the VEE is complete and material inside the VEE is at a uniform 1200ºF, the plate will move down as a result of expansion in the longitudinal direction, below the neutral axis



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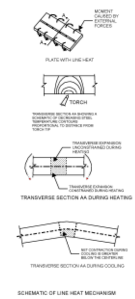
Line Heat Pattern

- Line heats are used to bend a member about its weak axis, usually following a yield line
- External constrains are often used in conjunction with line heats, although movement can be produced without external constraint such as a jacking force
- Upsetting occurs on the torch side of the material
- Cool material on the opposite side of the torch acts as a constraint
- During cooling the contraction below the plate centerline creates a bending moment and permanent deformation occurs without altering the steel properties, or producing unwanted strain hardening



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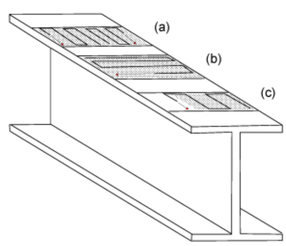
Strip Heat Patterns

- Compliment VEE heats
- Accomplished similar to VEE heats, in a rectangular pattern
- Orientation of the serpentine pattern can affect the strip heats' weak axis deformation
- Alternating heat application location can minimize weak axis bending



SCHEMATIC OF A STRIP HEAT APPLIED AT THE TOP FLANGE OF A WIDE FLANGE BEAM

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Fundamental Damage Patterns

- In most cases, damage is a combination of the four fundamental damage types
- Use of sequentially applied heat patterns for each type can be effective for this type of damage
- Primary and stiffening elements
  - Primary: damaged elements being straightened about their strong axis
  - Stiffening: damaged elements being straightened about their weak axis
- Primary: VEE heats
- Stiffening: Line and Strip heats

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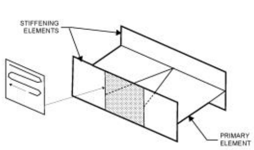
Category S Damage

- Refers to strong axis deformations
- Combination of a VEE heat and a Strip heat
- VEE heat is applied first, followed by a strip, bot. flange at the open end of the VEE
- The strip width is always equal to the width of the VEE open end
- The strip allows the VEE to close during cooling without constraint from the stiffening element (flange)



HEATING PATTERNS FOR WIDE FLANGES BENT ABOUT THEIR MAJOR AXIS (CATEGORY S)

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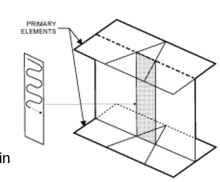
Category W Damage

- Bending about the weak or minor axis
- The VEE heats are on the flanges, and the Strip heat is on the web
- Similar rules as for the type S damage, in that the VEE widths match at the Strip intersection.
- VEE heats are applied simultaneously followed by the Strip heat
- The vee heats prevent the flanges from constraining the upsetting and contraction weak axis straightening in the web



HEATING PATTERN FOR WIDE FLANGE BENT ABOUT MINOR AXIS (CAT W)

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Heat Pattern Sequencing

- Sequencing of different pattern types is essential to develop a successful straightening design.
- The following slide will show an example of the sequencing used for the Campus Road Bridge repair
- A weak axis type W repair is followed by a type L "local" damage repair
- A fundamental concept in heat straightening is to complete one straightening type (W), then move on to the next (L)

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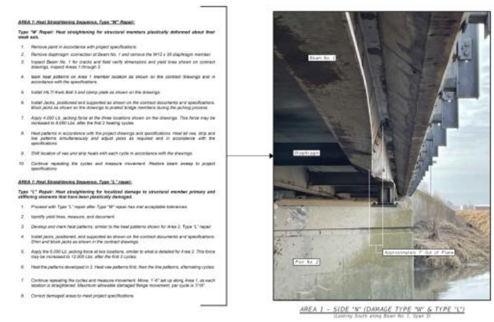

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Heat Pattern Combinations

- The Campus Road Bridge involved type W and type L repairs
- It was necessary to combine the repair types and incorporate sequencing to affect a successful repair
- The use of internal and external constraints was developed
- The non-composite design also had to be considered and additional external constraints employed to ensure deck integrity during jacking
- The following slide shows an example of pattern development to be followed in the sequencing plan

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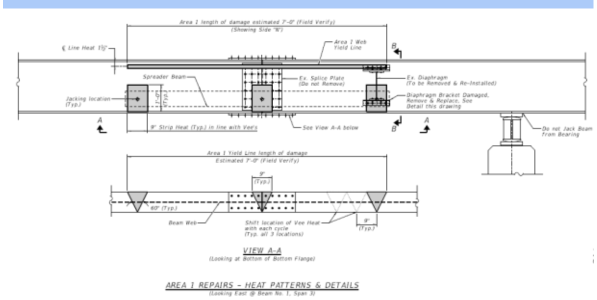
Heat Pattern Combinations



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Quantifying Damage Assessment

- Site visit and special inspection of the bridge damage
- Measurements and computational assessment
  - Analyze degree of damage and maximum strain
  - Structural analysis of damaged system
  - Select applicable areas for heat straightening repair
  - Select heating patterns and parameters
  - Develop restraining load plan (constraint) and design jacking forces
  - Estimate heating cycles required to straighten members
- The following slide shows the Campus Road degree of damage analysis for Area 1 type W damage

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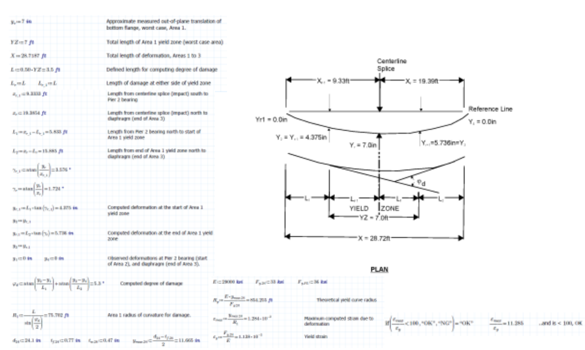

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Damage Level Limits

- Application of heat tends to restore the original material properties so long as the lower critical transition temperature or the tempering limit is not exceeded.
- Current research and testing indicate that heat straightening can be successfully done for strains up to 100% of the material's yield strain

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Heat Straightening Effects on Yield and Tensile Strength

- Little change occurs in the modulus of elasticity after multiple VEE heat cycles
- Small increases in yield (10%) and tensile stress (4%)
- Up to 25% decrease in ductility (plastic deformation without failure)
- The small but significant increase in yield and tensile stress in members subjected to multiple heat cycles indicates that heat straightening has a heat-treating effect on the repaired steel.
- CVN tests on samples that have been heat straightened over multiple cycles indicate a significant loss of toughness for mild carbon steel. Quench tempered steel was not significantly affected for toughness

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Heat Straightening Residual Stresses

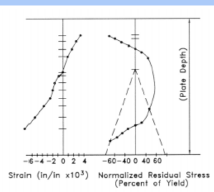

Fig. 14. Experimental strain and theoretical residual stress distribution for ⅔ depth, 45° vee heated plate subjected to 1000°F temperature (Roeder, 1985).

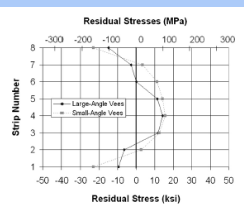

Fig. 15. Average residual stress values for vee heated plates which were originally undamaged.

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Developing Jacking Loads

- Area 1, type W repair jacking load estimate
- Damaged section properties are developed
- Yield line length from field inspection
- Use reduced yield strength $0.25F_y$
- Develop required jacking moment using plastic section modulus and modified yield strength
- Develop initial jacking force at $0.25F_y$ for the first two cycles
- Jacking force for the remaining cycles $0.50F_y$. $0.50F_y$ corresponds to the full estimated strength of the steel at the lower transition phase temperature of 1200ºF

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Jacking Force Estimate

2.5.1 Develop jacking loads for Area 1, Type W repair, using vee heats on flange (primary element)

$L_{1.w} = 7\ ft$ — Primary beam element (bot. flange) yield line length

$b_{f.24} = 9.02\ in$

$Z_{y.24} := \frac{t_{f.24} \cdot b_{f.24}^2}{4} = 15.662\ in^3$ — Flange primary plastic section modulus

$M_{p.f} := Z_{y.24} \cdot F_{y.24} = 516.842\ kip \cdot in$ — Flange plastic moment

$M_{j1.2} := 0.25 \cdot M_{p.f} = 129.21\ kip \cdot in$ — Jacking moment for the first two heat cycles

$M_j := 0.50 \cdot M_{p.f} = 258.421\ kip \cdot in$ — Jacking moment

$\theta := 60°$ — Vee heat angle

$F_{j1.2} := \frac{8 \cdot M_{j1.2}}{L_{1.w}} = 12.306\ kip$ — Jacking force required for first two cycles, assuming fixed end moment for Area 1

$F_{j1} := \frac{8 \cdot M_j}{L_{1.w}} = 24.612\ kip$ — Area 1 jacking force

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Estimating the Number of Heat Cycles

- The steel bridge beam for Campus Road is considered composite for the estimate of heat cycle duration
- Considering the jacking load, a change in angle of the deformed web is computed for each cycle
- The total angle of sweep required to affect the repair is considered from the damage assessment calculation
- A ratio of the total sweep angle to the angle swept in one cycle per VEE heat will determine the number of cycles
- Specifications for the minimum time between cycles for cooling and the maximum heating rate are also used to develop the time estimate.

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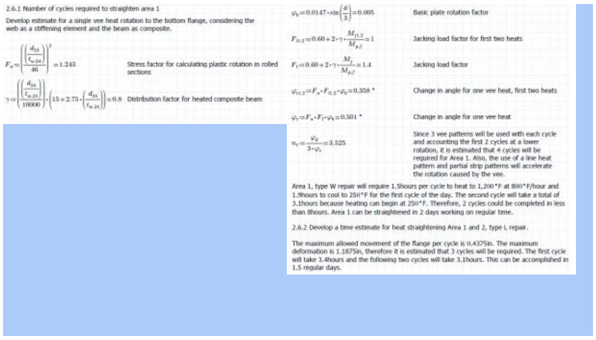

2.6.1 Number of cycles required to straighten area 1

Develop estimate for a single vee heat rotation to the bottom flange, considering the web as a stiffening element and the beam as composite.

$F_a := \left(\frac{\left(\frac{d_{24}}{t_{w.24}}\right)}{46}\right)^2 = 1.243$ Stress factor for calculating plastic rotation in rolled sections

$\gamma := \left(\frac{\left(\frac{d_{24}}{t_{w.24}}\right)}{10000}\right) \cdot \left(15 + 2.75 \cdot \left(\frac{d_{24}}{t_{w.24}}\right)\right) = 0.8$ Distribution factor for heated composite beam

$\varphi_b := 0.0147 \cdot \sin\left(\frac{\theta}{3}\right) = 0.005$ Basic plate rotation factor

$F_{f1.2} := 0.60 + 2 \cdot \gamma \cdot \frac{M_{j1.2}}{M_{p.f}} = 1$ Jacking load factor for first two heats

$F_j := 0.60 + 2 \cdot \gamma \cdot \frac{M_j}{M_{p.f}} = 1.4$ Jacking load factor

$\varphi_{c1.2} := F_a \cdot F_{f1.2} \cdot \varphi_b = 0.358\ °$ Change in angle for one vee heat, first two heats

$\varphi_c := F_a \cdot F_j \cdot \varphi_b = 0.501\ °$ Change in angle for one vee heat

$n_t := \frac{\varphi_d}{3 \cdot \varphi_c} = 3.525$ Since 3 vee patterns will be used with each cycle and accounting the first 2 cycles at a lower rotation, it is estimated that 4 cycles will be required for Area 1. Also, the use of a line heat pattern and partial strip patterns will accelerate the rotation caused by the vee.

Area 1, type W repair will require 1.5hours per cycle to heat to 1,200°F at 800°F/hour and 1.9hours to cool to 250°F for the first cycle of the day. The second cycle will take a total of 3.1hours because heating can begin at 250°F. Therefore, 2 cycles could be completed in less than 8hours. Area 1 can be straightened in 2 days working on regular time.

2.6.2 Develop a time estimate for heat straightening Area 1 and 2, type L repair.

The maximum allowed movement of the flange per cycle is 0.4375in. The maximum deformation is 1.1875in, therefore it is estimated that 3 cycles will be required. The first cycle will take 3.4hours and the following two cycles will take 3.1hours. This can be accomplished in 1.5 regular days.

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Questions

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