

Heat Straightening of Damaged Steel Members

Steel bridge members get bent, twisted and buckled by over-height vehicle strikes, construction and handling mishaps, overloads, earthquakes and fires. Heat straightening lets an owner restore many of these members in place, often without replacing steel or shoring the span, if the repair is engineered rather than improvised. This course follows the FHWA Guide for Heat-Straightening of Damaged Steel Bridge Members (FHWA-IF-08-999, R. Richard Avent, August 2008), the final draft of the AASHTO guidelines, and notes where the newer FHWA Manual for Heat Straightening, Heat Curving and Cold Bending of Bridge Components (FHWA-HIF-23-003, March 2023) updates it. It covers how heat straightening works, the temperature limits by steel type, the vee, line, edge and spot heating patterns, restraint and jacking limits, how to measure damage and decide between repair and replacement, and how to specify and inspect the work. Temperature, strain and jacking limits are quoted from those two documents with their sections. Worked numbers in the examples are illustrative and computed for this course, not from a real bridge.

Learning objectives

- Describe how heat straightening works
- State temperature limits
- Select heating patterns
- Assess when replacement is needed

Why heat straightening matters

Damage to steel bridge members is a perennial problem. FHWA-IF-08-999 lists the usual causes as overload, vehicle impact, handling, earthquake and fire. When a fascia girder takes a hit, the owner has three broad choices: replace the damaged member or part of it, strengthen or splice around the damage, or straighten the steel back to shape.

Heat straightening is often the fastest and cheapest of the three. It can usually be done in place, often without temporary shoring, without ordering new steel or making new connections, and with limited lane closures. The guide traces it back almost half a century, mostly as the craft of a few experienced technicians, and says it was long seen as more art than science. Research from the 1980s through the 2000s, much of it by Avent and colleagues, gave engineers the numbers they need to design and specify a repair.

The guide frames the engineering problem as two questions:

- Are there heat-straightening procedures that do not compromise the structural integrity of the steel?
- If so, how can the repair be engineered so the structure is safe both during and after the work?

This course is organized around the answers: controlled temperatures, the right patterns, limited restraint forces, sound damage assessment, and inspection that enforces all three.

Damage categories

FHWA-IF-08-999 (Sec. 1.2) sorts damage into four fundamental categories. Real accidents usually combine them, but each category has its own heating pattern, so naming the category is the first step in planning a repair.

- **Category S (strong axis).** Bending about the major axis. In a rolled or built-up shape, the web bends in its plane with one flange in compression and one in tension. The compression flange and web may also buckle locally.
- **Category W (weak axis).** Bending about the minor axis, such as a flange pushed sideways by a truck strike or a bracing member bent flat.
- **Category T (twisting).** Torsion about the member's long axis. If neither flange is braced, the flanges bend plastically in opposite directions and the web often stays below yield. If one flange is restrained, as with a composite girder whose top flange is locked into the deck, the free bottom flange deforms and the web may yield too.
- **Category L (local).** Localized flange or web buckles, web crippling, damage at bracing connections, and bends or crimps in individual plate elements.

A typical over-height strike on a composite fascia girder shows Category W or T damage in the bottom flange plus Category L buckles in the web and at diaphragm connections. The guide's advice (Sec. 3.4.4) is to tackle one basic damage type at a time: for example, remove the Category W damage before addressing the Category L damage.

Heat straightening versus hot mechanical straightening and hot working

The guide defines heat straightening (Sec. 2.1) as applying controlled heat in specific patterns to the plastically deformed regions, in repeated heating and cooling cycles, so the steel straightens gradually. Force is not the main tool. Three conditions must hold throughout:

1. The steel temperature stays below **(a)** the lower critical temperature, the lowest temperature at which molecular (phase) changes occur, and **(b)** for quenched and tempered steels, the temper limit.
2. Stresses from applied external forces stay below the yield stress of the steel in its heated condition.
3. Only the regions near the plastically deformed zones are heated.

When those conditions are met, the guide says material properties change relatively little and the steel performs essentially as before.

The guide warns against two methods that are often confused with heat straightening:

- **Hot mechanical straightening** heats the steel and then applies force well above yield, so the member moves a lot in one cycle. Results are unpredictable, and little research exists on it. Concerns include fracture during straightening, damaged material properties, and buckles, wrinkles or crimps. The guide calls it unproven and limits it to non-load-carrying elements when replacement or other methods are not viable.
- **Hot working** combines large forces with heat well above the lower critical temperature, often to a cherry-red glow. Results are highly unpredictable and may include fracture, irreversible changes in microstructure, brittleness and distortion. The guide says hot working *should not be used* to repair damaged structural steel.

The guide also cautions that some practitioners over-jack and over-heat and still call it heat straightening. Specifications and inspection have to enforce the difference.

How heat straightening works

Heat straightening relies on two properties of steel, as FHWA-IF-08-999 explains in Sec. 2.2. First, steel stretched or compressed past yield does not return to its original shape; it stays partly elongated or shortened. Second, steel heated to modest temperatures, which the guide gives as 700 to 1300°F (370 to 700°C), expands at a predictable rate and its yield strength drops substantially while it is hot.

The guide illustrates the mechanism with a short bar clamped snug in a rigid fixture. When part of the bar is heated, it tries to expand lengthwise, but the fixture stops it. The heated metal, which is now weaker, expands more than it otherwise would across its width and through its thickness, and yields locally into a slight bulge. When the heat is removed, the bar cools and contracts in all three directions. The clamp cannot stop the bar from shortening, so the bar ends up slightly shorter than it started, with a small permanent bulge. That permanent thickening is called **upsetting**, and the redistribution of material is plastic flow. Repeating the cycle of clamping, heating and cooling can shorten the bar significantly.

A bent member is straightened the same way, by shortening the fibers that were stretched when it was damaged. A vee heat on a plate bent about its strong axis is the clearest example. The torch starts at the apex of a vee-shaped area and works toward the open end. The cool steel around and ahead of the torch confines the hot metal, so it upsets through the thickness. Because the vee is widest at its open end, more material is upset there, and on cooling the plate contracts more at the open end than at the apex. The net effect is a small rotation that closes the vee and reverses part of the damage.

Each cycle moves the steel only slightly, so heat straightening is by nature incremental. The guide notes that 20 or more heating cycles are sometimes needed. That slow, controlled movement is what keeps the steel's properties largely intact, and it is why patience is part of the specification.

The guide names three keys to the process:

- 1. Select heating patterns, and a sequence, that fit the damage.
- 2. Control the heating temperature and the rate of heating and cooling.
- 3. Provide restraint during heating that can be relaxed or modified during cooling.

The rest of this course takes those keys in turn.

Temperature limits by steel type

Temperature control is the core safety rule of heat straightening. Every number in this section was checked against FHWA-IF-08-999 and FHWA-HIF-23-003 for this course. Because the two documents and the AASHTO/AWS D1.5 Bridge Welding Code have changed over time, the governing limit on a project is the one in the owner's current specification, checked against the steel's mill certificate.

What the 2008 FHWA guide says

FHWA-IF-08-999 (Sec. 2.8) explains that plastic rotation per heat rises with temperature, up to at least 1600°F (870°C), so hotter heats move the steel faster. But hotter is not better:

- Out-of-plane distortion becomes likely and surface damage such as pitting occurs at 1400 to 1600°F (760 to 870°C).
- Above roughly 1300°F (700°C), the **lower phase transition temperature**, the steel's microstructure may change and its properties can be altered after cooling. Sec. 5.1 puts the phase transition at approximately 1330°F (720°C).

The guide therefore sets these maximum heating temperatures:

Steel	Maximum temperature	Basis given in FHWA-IF-08-999
Carbon steels and other non-quenched-and-tempered steels	1200°F (650°C)	Leaves about 100°F of margin below the lower phase transition, matching the error range found among experienced practitioners

A514 and A709 Grades 100 and 100W (Q&T)	1100°F	Minimum tempering temperature of 1150°F (620°C), leaving a 50°F (30°C) margin
A709 Grade 70W, quenched and tempered	1050°F (565°C)	Specified minimum tempering temperature of 1100°F (590°C), leaving a 50°F margin
HPS 70W produced by thermo-mechanically controlled processing (TMCP)	1200°F (650°C)	TMCP steel is not Q&T, so the carbon-steel limit applies

The guide also notes that AASHTO/AWS D1.5 (1996) specified 1100°F (590°C) for Q&T steels and 1200°F (650°C) for all others.

One caution about the 2008 document: it gives the Celsius value of the 1100°F Q&T limit as 590°C in Sec. 2.8 and 3.4, as 595°C in Sec. 5.2.1, and as 620°C in its model specification. The Fahrenheit value, 1100°F, is the same in all three places and agrees with D1.5. This course teaches 1100°F, and the discrepancy is listed in the course flags.

What the 2023 FHWA manual adds

FHWA-HIF-23-003 (Sec. 2.2.7) quotes AASHTO/AWS D1.5 (2015), which it notes is incorporated by reference at 23 CFR 625.4(d)(2)(i), as setting:

- **1,200°F** for non-Q&T steels: ASTM A709 Grades 36, 50, 50W, 50S and HPS 50W.
- **1,100°F** for Q&T steels: ASTM A709 Grades HPS 70W and HPS 100W.

The manual adds practical guidance:

- Metallurgists may suggest not exceeding the steel's published nominal tempering temperature. If that temperature is below 1,100°F, heat below the tempering temperature. The tempering temperature can be found on the mill certificate or obtained from the mill.
- For ASTM A913 steel, about 1,100°F is typically suggested for Grades 50, 60, 65 and 70, and 1,000°F for Grade 80, based on the maximum tempering temperature used for those grades.
- Research by Yu (2006) found that heating near high-strength bolts should be limited to 800°F to prevent a permanent loss in fastener assembly strength, unless the bolts are replaced afterward.

The manual states that its summary table mixes values that are Federal requirements with values that are not. Treat the D1.5 values as the requirement and the others as guidance unless the owner adopts them.

Practical rule for this course

Identify the steel from the plans, shop drawings or mill certificates. If it is a quenched and tempered grade, or the grade is unknown and could be Q&T, do not use the 1200°F limit until the grade and tempering temperature are confirmed. Watch for bolted connections in the heated area. Write the limit for each member into the repair plan, not just "per D1.5."

Measuring temperature in the field

Setting a limit is easy; holding it in the field is not. FHWA-IF-08-999 (Sec. 5.2.1) reports that knowledgeable practitioners commonly misjudged heating temperature by about 100°F (55°C), and sometimes by as much as 200°F (110°C). That variability is one reason the 1200°F limit sits about 100°F below the phase transition.

The guide lists three ways to monitor temperature: watching the steel's color, temperature-indicating crayons or pyrometers, and infrared non-contact thermometers. The model specification (3.2) requires the contractor to use one or more of the following for routine, documented temperature checks:

- Temperature-sensitive crayons.
- A pyrometer.
- An infrared non-contact thermometer.

Color is still the technician's moment-to-moment guide, and the guide (Sec. 2.11.3) explains why it is tricky:

- At about 1200°F, steel shows a satiny silver color, but torch flame reacting with surface impurities often hides it.
- The guide suggests checking the surface for a 3 to 5 second "soak time" after the flame leaves an area.
- In daylight or bright indoor light, the silver color is easier to read and no dull red shows. In shadow, on overcast days or under limited artificial light, steel at the same temperature gives off a dull red glow.
- A No. 3 welding lens, which the guide recommends for the torch operator, can mask subtle colors, so a second observer without goggles may be needed.

The guide's general rule is simple: **if red is visible in normal lighting, the steel is too hot.** Overheating can create brittle, fracture-sensitive zones and could lead to sudden failure, so constant attention is required. An inspector should verify the contractor's temperature checks independently, especially in the first few cycles, before trusting the crew's eye.

The four basic heating patterns

FHWA-IF-08-999 (Sec. 2.3) describes four basic heating patterns for flat plates. Because most bridge members are assemblies of plates, these patterns are combined to suit each shape and damage category.

Vee heat

The vee heat is the basic pattern for straightening a plate bent about its strong axis (Category S). The torch starts with a small spot at the apex of a vee-shaped area. When the steel reaches temperature, the guide says usually around 1200°F for mild carbon steel, the operator advances the torch in a serpentine path toward the open end, heating the vee progressively from top to bottom.

During heating, the plate first moves the "wrong" way, because the metal is expanding. Once the heat is complete and the whole vee is hot, the plate has moved downward as the material below the neutral axis expands. As it cools, the vee contracts more than it expanded, so the plate ends with a net movement that closes the vee. The vee always points toward the side that needs to shorten: the open end is placed on the edge that was stretched by the damage, which is the convex side.

Vees usually extend over the full depth of the plate element, but partial-depth vees can be useful. With a partial-depth vee, the open end should still reach the edge of the plate; only the apex moves inward. Three-quarter and half-depth vees are the most common.

Edge heat

For a smooth, gentle bend, a line near the edge of a member is heated, continuously or intermittently depending on the curvature wanted. This pattern is often used in the shop to heat-curve rolled shapes. The guide's figure note says edge heats are applied about 2 in. from the edge for inelastically stretched edges and for thermally cut flanges with small notches.

Line heat

A line heat repairs a plate bent about its weak axis, which is the typical yield line in a flange pushed sideways. It is a single straight torch pass along the yield line. The cool steel ahead of the torch restrains expansion, and because the temperature falls off through the thickness, more upsetting occurs on the torch side. That side therefore contracts more on cooling and the plate turns concave toward the torch. **So the heat goes on the convex side of the bent plate.** External forces that bend the plate about the yield line magnify the movement. Torch speed matters a lot, because it sets the temperature reached.

Spot heat

A spot heat warms a small round area by moving the torch in a slow, widening circle. It upsets the metal through its thickness, restrained by the cool steel around it, and leaves radial tensile stresses on cooling. Spot heats are mainly used for local bulges and crimps (Category L), not for overall member bends.

Patterns for rolled and built-up shapes

The guide (Sec. 2.5) builds patterns for whole members out of the plate patterns, matched to the damage category.

Strong-axis bends (Category S)

For a wide-flange beam bent about its strong axis, the yield zone runs through the web and both flanges near the point of maximum curvature. The usual pattern is a vee heat in the web with its open end toward the stretched flange, combined with a strip heat across the stretched flange where it meets the open end of the vee. The guide shows a common sequence in which the vee goes first, followed immediately by the strip. It also states that the research does not yet support mandating one sequence over another, and that the practitioner's experience is the most reliable guide (Sec. 2.11.6).

Weak-axis bends (Category W)

For bending about the weak axis, the flanges are the primary elements bent about their strong axis, so vee heats go in the flanges with their open ends on the stretched edge. The web may need a line heat or no heat, depending on whether it yielded. Channels and angles follow the same logic: identify which legs were bent about their strong axis and which about their weak axis, then use vees and lines to match.

Twisting (Category T)

For twisting damage, each flange is treated for the direction it actually bent, often using vee heats in opposite directions on the two flanges. Where one flange is held by a composite deck, the repair concentrates on the free flange and any web yielding. The guide notes that combinations of damage are usually handled by working on one basic pattern at a time.

Local damage (Category L)

Local flange and web buckles and bends or crimps in plate elements are repaired with combinations of line heats, spot heats and small vees, usually with jacks or clamps to guide the plate back. Bulges in webs are often worked from the edges toward the center. Local damage is where hot mechanical straightening is most tempting, because a buckle can be popped back with a large jack, and where the inspector most needs to watch the jacking force.

Choosing vee depth, vee angle and spacing

FHWA-IF-08-999 gives specific guidance on vee geometry (Sec. 3.4.4 and Sec. 5).

- **Vee depth.** In general, the vee should extend across the full width of the plate being straightened. The guide says partial-depth vees do not reduce member shortening, despite some speculation that they do, and that half-depth vees are mainly for repairing local damage. Plate tests found that vee depths between 75% and 100% of plate width have little effect on plastic rotation.
- **Vee angle.** Make the vee as large as is practical, because the movement per heat is roughly proportional to the vee angle. But if the open end is too wide, out-of-plane distortion often occurs, and the vee must be small enough to heat quickly so that uneven cooling is limited. The rule of thumb is to keep the open end at about one-third to one-half the plate width, but not more than about 10 in. (254 mm). The guide notes that this corresponds roughly to vee angles of 20 to 30 degrees. Elsewhere (Sec. 3.1) the guide adds that the 10 in. limit applies to plates about 1 in. thick and that thinner plates call for smaller vees to avoid local buckling.
- **Vee angle formula.** If the open-end width V and plate width W are chosen, the vee angle is $\theta = 2 \tan^{-1} (V / 2W)$ (Eq. 3.9).
- **Simultaneous vees.** More than one vee can be heated at the same time if they are spaced at least one plate width W apart. The model specification (3.6) says the clear spacing must be greater than the width of the plate element.
- **Shifting.** Vee heats should be shifted around the yield zone on successive cycles (model spec. 3.5), not placed in the same spot every time.

Illustrative example: vee angle

The following numbers are illustrative, computed for this course. A damaged bottom flange is 16 in. wide and 1 in. thick, bent about its strong axis. Using the guide's rule of thumb, the open end of the vee should be between $W/3 = 5.3$ in. and $W/2 = 8$ in., and not more than 10 in. Choosing $V = 8$ in. gives $\theta = 2 \tan^{-1} (8 / 32) = 2 \times 14.0^\circ = 28^\circ$, which is inside the 20 to 30 degree range the guide cites. A 6 in. open end would give $\theta = 2 \tan^{-1} (6 / 32) = 21^\circ$. The 8 in. vee will move the flange more per cycle; the 6 in. vee will heat faster and has less risk of distortion. If two simultaneous vees are wanted, their clear spacing must exceed 16 in.

Restraining forces and jacking limits

Restraint is what makes heat straightening efficient, and over-restraint is what makes it dangerous. FHWA-IF-08-999 (Sec. 2.10) uses "restraining forces" to mean both externally applied forces, usually jacks or come-alongs, and internal restraint from the structure's redundancy and self-weight. A restraining force usually applies a bending moment that tends to close the vee. It does the same job as the cool steel ahead of the torch: it limits free lengthwise expansion during heating, so more of the hot metal upsets through the thickness. The guide reports that plastic rotation per heat is generally proportional to the jacking ratio, and that jacks can greatly reduce the number of heating cycles needed.

Why the limit is 50% of capacity

The guide reasons from the drop in strength at temperature. At 1200°F, it says, the yield stress is reduced by about 50%. A restraining force that produces stresses of 50% of the ambient yield stress in the heated zone therefore puts that zone near initial yield while it is hot, and anything higher pushes the work into hot mechanical straightening. (The 2023 manual, FHWA-HIF-23-003, puts the yield stress at 1,200°F at about 40% of its original value and the modulus at about half, which makes the same point more strongly.) The guide calls the 50% limit somewhat conservative, because the whole cross section is never at 1200°F at once.

Five criteria for restraint

The guide lists criteria that apply to internal and external restraint alike:

1. Restraint should be passive during heating: applied before heating and not increased by external means during heating or cooling.
2. Restraint should not impede contraction during cooling.
3. Restraint should not cause local buckling of the compression element during heating.
4. Restraint should not make the structure unstable, either by forming plastic hinges or by causing member instability.
5. Restraint should be limited so that the maximum moment in the heated zone does not cause stresses above 50% of the ambient-temperature yield stress.

In practice, the guide says, this means keeping the vee angle small enough to avoid local buckling, setting external forces before heating so they relieve themselves as the steel contracts, and basing the maximum external force on a structural analysis of the whole structure that accounts for the heated member's reduced strength and stiffness.

The model specification limits

The guide's model specification turns those criteria into numbers. The sum of jacking-induced moments and estimated residual moments must be less than 50% of the member's plastic moment capacity, M_p . As an alternative to estimating residual moments, the jacking moment alone can be limited to 25% of M_p during the first two heating cycles, after which the 50% limit may be used again. The contractor must determine and document the maximum jacking force at each damage location, plus the proposed sequence of jacking and heating, and submit it to the Engineer for acceptance before starting. Changes during the work must also be submitted. Jacks must be calibrated and gauged, and the maximum force can also be controlled by limiting the deflection the jack produces.

Why over-jacking is dangerous

The guide warns that over-jacking can cause over-correction, buckling, or brittle fracture during or shortly after heat straightening. It can also leave micro-cracks that are hard to detect and could severely reduce fatigue resistance. It also explains that a lack of movement is not a reason to push harder. If the steel does not move, do several more cycles in new spots within the yield zone, since residual stresses or restraint from the structure may be resisting the movement. If the problem continues, re-analyze the jacking layout. In the guide's words, over-heating or over-jacking is not a solution.

Illustrative example: setting a jacking force

All numbers in this example are illustrative, computed for this course, and not from a real bridge.

A rolled W24x76 fascia beam (plastic section modulus about $Z_x = 200 \text{ in.}^3$, a tabulated AISC value used here for illustration) of Grade 50 steel was struck and bent about its strong axis at midspan. The plastic moment is:

$$M_p = F_y \times Z_x = 50 \text{ ksi} \times 200 \text{ in.}^3 = 10,000 \text{ kip-in.} = 833 \text{ kip-ft.}$$

The engineer decides not to estimate residual moments for the first cycles and uses the 25% alternative:

$$M_j \text{ (cycles 1 and 2)} \leq 0.25 \times 833 = 208 \text{ kip-ft.}$$

The jack is set between the beam and a reaction frame, acting at 6 ft from the vee on a cantilevered lever arm in the plan. The maximum jack force for the first two cycles is:

$$P \leq 208 \text{ kip-ft} / 6 \text{ ft} = 34.7 \text{ kips; the plan rounds down to 34 kips.}$$

From the third cycle on, the 50% limit may be used, but it applies to the jacking moment *plus* the estimated residual moment. If the engineer estimates the residual moment from the damage at about 15% of M_p , the jacking moment may rise to $(0.50 - 0.15) \times 833 = 292$ kip-ft, or $P \leq 48.6$ kips. This is still subject to a check of the whole structure in its weakened, heated condition, including deck and diaphragm restraint, stability of the compression flange, and what happens to adjacent girders.

The point of the example is the process: compute M_p , pick the limit the specification allows, convert it to a jack force for the actual geometry, write it into the plan, and check the gauge in the field. The inspector should be able to read the limit off the plan and compare it with the calibrated gauge at any time.

Heating sequence, cycles and cooling

Heat straightening is a cyclic process, and movement happens gradually by contraction during cooling. Several rules govern the cycle.

- **Single pass.** The model specification (3.3) requires material to be heated in a single pass following the specified pattern. Going back over a pattern that has already been heated interrupts the contraction process.
- **Stay on the pattern.** Yield zones occur where curvature is sharpest. The guide says some practitioners tend to heat a broader area, but that more heat here means less movement: stick with the recommended patterns and do not expand them.
- **Cool before reheating.** Heated material must cool below 250°F (120°C) before it is reheated (model spec. 3.3; FHWA-HIF-23-003 repeats the 250°F suggestion).
- **Expect variation.** The guide notes that the first cycles often move the member more than later ones, and that movements per heat can vary considerably because so many variables are hard to control.

Cooling

The guide (Sec. 2.11.8) says air cooling at ambient temperature is the safest method. Rapid cooling is dangerous if the steel has been overheated and may produce brittle "hot spots." Once the steel is below the lower phase transition temperature, however, rapid cooling is not harmful. Many practitioners let the surface cool below about 600°F (315°C) before speeding up cooling, which ensures that the interior has also cooled. Cooling can then be sped up with compressed air or, faster, with a water mist. For mist, the guide calls for an applicator that keeps the technician at a safe distance, protective clothing and goggles, and a way to safely dispose of the waste water, since steam can cause burns and runoff can wet areas that still need heating.

Torch tips

The goal of tip selection (Sec. 2.11.1) is to bring the steel near the tip to temperature quickly through its full thickness, not just at the surface. A tip that is too small cannot heat through thick plate; a tip that is too large heats so fast that temperature and distortion are hard to control. The guide's Table 1 recommends tip size and type by plate thickness, moving from single-orifice tips on thinner plates to rosebud tips on thicker ones. Heat sinks such as stiffeners and the web-flange junction slow the torch; the last pass along a free edge of a vee is usually quick, because the heat wave nearly catches up with the torch.

Assessing the damage

FHWA-IF-08-999 (Ch. 3) treats a heat-straightening repair like any other design. The engineer selects a trial repair, analyzes the structure, sets the repair parameters or checks the capacity after repair, and then writes details and specifications. The

guide says this step is often overlooked. Heat straightening is not the answer for every damage situation, and the engineer's job is to decide whether it applies.

The guide lists what to consider: the condition of the rest of the structure and other planned repairs, the degree of damage, any fractures, the cause of the damage and the likelihood of it happening again, access, and the effect of the repair on material properties. Once heat straightening is chosen, the plan must set traffic control, contractor access and work areas, permitted work hours, typical heating patterns, maximum restraining forces and their locations, and the maximum heating temperature.

Degree of damage

The guide measures damage in two ways (Sec. 3.3.2):

- **Angle of damage, ϕ_d .** The angle of permanent deformation at the plastic hinge. It is measured with offsets from a taut line, laser or straightedge, using the undamaged regions on either side as reference lines. With offsets y_1 and y_2 measured a distance L_1 apart on one side and y_3 and y_4 a distance L_2 apart on the other, $\phi_d = \tan^{-1} [(y_2 - y_1)/L_1] + \tan^{-1} [(y_3 - y_4)/L_2]$ (Eq. 3.1). It can also be measured with a protractor on a photograph taken perpendicular to the plane of the bend.
- **Maximum strain ratio, μ .** The ratio of the maximum damage strain to the yield strain. With offsets measured at equal spacing L in the damaged zone, the radius of curvature is approximated by $1/R = (y_{(r-1)} - 2y_{(r)} + y_{(r+1)}) / L^2$ (Eq. 3.2). Strain is $\epsilon_{\max} = y_{\max} / R$, where $y_{\max}$ is the distance from the centroid to the extreme fiber (Eq. 3.6), and yield strain is $\epsilon_y = F_y / E$ (Eq. 3.7). So $\mu = E y_{\max} / (R F_y)$ (Eq. 3.8).

The guide notes that these equations assume a constant radius of curvature over the damaged length. That works well for a smooth bend; for an irregular one, measure only the worst portion with the three-point offset method.

The 100 times yield strain limit

Research data show that heat straightening can succeed on steel with plastic strains up to 100 times the yield strain, ϵ_y . The guide says there is reason to believe larger strains can also be repaired, but because no research data exist beyond $100\epsilon_y$, engineering judgment is required there. The model specification (2.4) says steel with strains up to 100 times yield strain may be heat straightened, and for higher strains the Engineer decides. Cracks, strains above $100\epsilon_y$, or other serious defects may change the contract scope (model spec. 2.5).

Illustrative example: computing the strain ratio

All numbers in this example are illustrative, computed for this course.

A bottom flange 16 in. wide was pushed sideways by a truck, bending it about its strong axis (the plate's in-plane axis), so $y_{\max}$ is half the flange width: 8 in. A taut line along the flange gives three offsets at 12 in. spacing through the sharpest part of the bend: 1.10 in., 1.85 in. and 1.10 in.

$1/R = (1.10 - 2 \times 1.85 + 1.10) / 12^2 = (-1.50) / 144 = -0.0104$ per in. The magnitude gives $R = 96$ in.

$\epsilon_{\max} = y_{\max} / R = 8 / 96 = 0.0833$.

For Grade 50 steel, $\epsilon_y = F_y / E = 50 / 29,000 = 0.00172$.

$\mu = 0.0833 / 0.00172 \approx 48$.

The strain ratio is about 48, well under the guide's $100\epsilon_y$ limit, so heat straightening is a candidate if the other criteria are met. If the middle offset had been 3.0 in., $1/R$ would be $3.80/144$, $R \approx 37.9$ in., $\epsilon_{\max} \approx 0.211$ and $\mu \approx 123$. That exceeds 100, so the Engineer would need to justify heat straightening by judgment, consider replacing the damaged portion, or both.

The angle of damage gives a quick cross-check. If offsets on the two undamaged sides show slopes of 3.0 in. over 48 in. and 2.5 in. over 48 in., $\phi_d = \tan^{-1}(0.0625) + \tan^{-1}(0.0521) = 3.6^\circ + 3.0^\circ = 6.6^\circ$. The guide uses the angle of damage mainly to estimate how many vee heats will be needed, since each vee heat produces a predictable plastic rotation for a given vee angle, temperature and jacking ratio.

Repair or replace

The degree of damage is the main criterion, but FHWA-IF-08-999 (Sec. 3.3 and 3.4.3) lists others that can tip the decision toward replacement or a combined repair.

- **Fractures.** A crack may require replacing part or all of a member. Sometimes the suspect region can be heat straightened and then repaired in place with mechanical connectors (bolted splice plates). In other cases a portion is replaced while the rest is straightened. Model spec. 2.1 lists ultrasonic and radiographic examination per AASHTO/AWS D1.5 among the inspection methods the Engineer may require.
- **Previous heat straightening.** A member that has already been heat straightened at the same location has less ductility to give (see the next section). The model specification (3.7) allows one repeat repair of a previously straightened region; further repairs are not recommended unless the Engineer approves.
- **Nicks, gouges and notches.** Abrupt discontinuities in the damage zone become stress risers when jacking and heat are applied. They should be noted and ground to a smooth transition before heat straightening.
- **Fire exposure.** If the steel stayed below the tempering temperature or the lower phase transition during the damage event, no permanent degradation is expected. If it may have been hotter, metallurgical tests should come first. The guide lists chemical analysis, grain size and microstructure, Brinell hardness, Charpy V-notch and tensile tests. Visual signs of high heat include melted mill scale, distortion, black discoloration, and cracking and spalling of nearby concrete. A significant increase in Brinell hardness compared with undamaged areas of the same member suggests heat damage. When fire distortion came from steel losing strength at high temperature, the guide says properties have probably been harmed, and repair decisions should rest on metallurgical analysis and expert opinion as well as the $100\epsilon_y$ limit.
- **Secondary members.** It is usually far cheaper to replace a badly damaged diaphragm or cross-frame than to straighten it. The guide recommends removing the diaphragm, especially if it would restrain the girder's movement, heat straightening the girder, and installing a new diaphragm.
- **Fracture-critical members.** Some have cautioned against heat straightening fracture-critical members. The guide says no research data support a ban but almost no fatigue testing has been done. If temperatures (including D1.5 limits) are carefully controlled, jacking forces are kept within limits, and notches and nicks are ground smooth, the guide sees no reason to expect unusual problems. It also calls for additional care on fracture-critical members to make sure the work is done properly.

Cost, time and traffic matter as well. The guide's list of design considerations includes cost, constructability, restoration of strength, longevity, time to complete, appearance and traffic impact. If the strike is likely to recur, for example on a low-clearance overpass that is hit repeatedly, the owner should weigh raising the structure, adding a sacrificial beam or warning system, or replacing the member, since each repeat repair degrades the steel further.

What heat straightening does to the steel

FHWA-IF-08-999 (Ch. 4) summarizes the research on how heat straightening changes steel. The findings explain both why a properly done repair is acceptable and why the limits exist.

Residual stresses

Heat-straightened plates show fairly consistent residual stresses, with peak compression of about 20 ksi (150 MPa) at the edges and tension of about half that at the center. In angles and channels, compression near yield occurs at the toes and heel, with high tension near the middle of each leg. In wide-flange beams, the maximum residual stresses approach yield in compression at the flange edges. The guide draws three conclusions:

- For compression members, these stresses are similar to those in welded built-up members. Because U.S. codes use a single column curve, no capacity reduction should be assumed.
- High tensile residual stresses can cancel the compression a jack is trying to create, so movement may be reduced or even reversed if the jacking moment does not overcome them. This is one reason "no movement" happens.
- Large compressive residual stresses also affect the buckling behavior of compression elements during later heats.

Mechanical properties after one repair

- The modulus of elasticity may fall by more than 25% in some heated regions.
- Yield stress may rise by as much as 20% in some cases, especially near the apex of vee heats. Overall, the long-term effect on yield is small but generally an increase.
- Tensile strength also rises, but at only about half the rate of yield stress.
- Ductility, measured as percent elongation, typically drops by about one-third.
- Charpy V-notch results vary considerably before and after repair, with no clear relationship established for first-time repairs.
- Fatigue-crack initiation thresholds rise with strength, and the guide judges the effect on fatigue to be small compared with the ductility loss, though some reduction in the fatigue limit could occur.

Within strain ratios of 100 or less, which covers most bridge damage, these changes do not depend on the degree of damage. Above 100, yield stress increases and elongation decreases in proportion to the strain ratio. So, except in heavily damaged areas, material properties should not be the main factor in deciding whether to heat straighten.

Repeated damage and repair

The number of damage/repair cycles at the same location matters a great deal. After two cycles, property changes stay modest. After four or eight cycles, the rise in yield and tensile strength and the loss of ductility are much larger, especially near the vee apex, and the material becomes increasingly brittle. The ratio of yield to tensile strength rises from about 68% in undamaged steel to about 78% after one cycle and about 88% after eight. In one full-scale study (Avent and Fadous, 1989), a girder cracked during a heat in its fourth damage/repair cycle. Connor, Kaufmann and Urban (2008) reached the same conclusion in full-scale fatigue and fracture testing. The guide's recommendation: **members re-damaged at the same location should not be heat straightened more than twice.**

Specifying and inspecting the repair

Because most repairs are done by contractors, FHWA-IF-08-999 (Sec. 3.1) describes a three-part team. The engineer selects and designs the repair. The field inspector, representing the owner, makes sure the work follows the plans and specifications, particularly the procedures that protect the steel. The contractor's crew carries out the work and must watch the structure's response and suggest changes, which may range from adjusting heating patterns and jacks to removing secondary members during the repair. The guide stresses ongoing, open communication among all three, because movements cannot always be predicted.

The guide's model specification gives an owner a starting point. Its key provisions, as summarized in this course, are:

- **Qualifications and documentation.** The contractor identifies and documents all yield zones, yield lines and associated damage before heating, by inspection or measurement (2.3).
- **Inspection before repair.** The Engineer may require nondestructive examination, including ultrasonic and radiographic testing per D1.5 (2.1), with costs negotiated separately (2.2).
- **Strain limit.** Up to 100% may be repaired; above that, the Engineer decides (2.4).
- **Temperature limits.** 1,200°F for carbon steels, 1,100°F for A514 and A709 Grades 100 and 100W, and 1,050°F for A709 Grade 70W (3.1), with documented checks by crayon, pyrometer or infrared thermometer (3.2). Update these to the current D1.5 and FHWA-HIF-23-003 as discussed earlier.
- **Heating practice.** Single pass per pattern; cool below 250°F before reheating (3.3); patterns matched to damage type and shape (3.4); vees shifted over the yield zone (3.5); simultaneous vees with clear spacing greater than the plate width (3.6); only one repeat repair of a previously straightened region without the Engineer's approval (3.7).
- **Jacking.** Jacking plus residual moments under 50% of M_p , or jacking alone under 25% of M_p for the first two cycles; documented maximum forces and sequence submitted before work; calibrated, gauged jacks; deflection limits as an alternative control (4.2 to 4.4).

Inspector's checklist

The following checklist is assembled for this course from the guide's requirements:

1. Steel grade and maximum temperature confirmed and written on the plan for each member; bolted connections in or near heated areas identified.
2. Damage survey with offsets, strain ratio and angle of damage on file; cracks checked and nicks and gouges ground smooth.
3. Jacking plan accepted; jack gauges calibrated; maximum force posted at each jack.
4. Temperature checks documented each cycle; no red visible in normal light.
5. Heats follow the specified patterns, in a single pass, shifted each cycle; cooling below 250°F before reheating; no water or air cooling until the surface is below about 600°F.
6. Movement recorded after each cycle; no increase in jack force during heating or cooling.
7. Final geometry checked against tolerances; repaired zone inspected for cracks; coating restored.
8. Repair history recorded in the bridge file so a future strike at the same spot is known to be a second repair.

Safety and a case study

The guide's safety precautions focus on the oxy-fuel equipment and work at height. Fuel tanks should be capped for transport, secured before work, and inspected for damage before each use, and lines and fittings checked for leaks with proper check

valves installed. The torch operator wears protective goggles, with a No. 3 lens recommended, plus gloves and protective clothing, keeps track of where the lit torch is pointed, and is in a stable, secure position before opening valves and lighting the torch. Scaffolding should be used properly, safety harnesses worn when working above the ground, and tanks and hoses secured before heat straightening begins. Traffic control is part of the plan, since repairs are often done over live lanes.

Illustrative case study

The following scenario is illustrative and assembled for this course; it does not describe a real bridge.

An over-height dump truck strikes the fascia girder of a two-span overpass. The girder is a composite rolled Grade 50 beam. The bottom flange is pushed laterally about 3 in. over a 10 ft length (Category W in the flange), the web shows a local bulge near a diaphragm (Category L), and the diaphragm connection plate is torn.

1. **Assessment.** Plans confirm A709 Grade 50, so 1,200°F applies. Offsets give a strain ratio of about 48 at the sharpest point. A magnetic particle check finds a crack in the diaphragm connection plate weld but none in the flange. There is no record of a previous repair.
2. **Decision.** The owner removes the bent diaphragm and its connection plate, heat straightens the flange and web, then installs a new connection plate and diaphragm, as the guide recommends for damaged diaphragms.
3. **Plan.** Vee heats in the flange with open ends on the stretched edge, open end limited to 8 in. on the 16 in. flange; spot and line heats for the web bulge after the flange is mostly straight; a lateral jack at the bottom flange limited to 25% of M_p for the first two cycles; documented infrared temperature checks.
4. **Execution.** About a dozen cycles over three night shifts bring the flange within tolerance. The inspector stops one shift when a technician starts tightening the jack during a heat. The plan is reviewed with the crew, and the jack is reset before the next cycle.
5. **Close-out.** The repaired zone is inspected for cracks, coating is restored, and the repair, with its location, is recorded in the bridge file. The owner also reviews vertical clearance signing, since a third strike at the same spot would exceed the guide's two-repair recommendation.

The lesson of the case study matches the guide's: the steel is restored safely when temperature, restraint and patterns are engineered, documented and enforced, and the repair history is kept for the next engineer.

Key takeaways

- Heat straightening uses repeated, controlled heating and cooling cycles in set patterns, not force, to restore plastically deformed steel.
- Temperature limits in FHWA-IF-08-999: 1200°F (650°C) for carbon and other non-Q&T steels, 1100°F for Q&T A514 and A709 Grades 100/100W, and 1050°F (565°C) for Q&T A709 Grade 70W. FHWA-HIF-23-003 quotes D1.5-2015 as 1,100°F for Q&T grades including HPS 70W and HPS 100W.
- If red is visible in normal lighting, the steel is too hot. Even experienced practitioners misjudge temperature by about 100°F.
- Limit the moment from jacking plus residual stress to 50% of the plastic moment, or the jacking moment alone to 25% of M_p for the first two cycles.
- Steel strained up to 100 times its yield strain may be heat straightened; beyond that, engineering judgment and the Engineer's approval are required.
- Let heated steel cool below 250°F (120°C) before reheating, and air-cool or use compressed air or mist only after the surface is below about 600°F.

- Do not heat straighten the same damage region more than twice; ductility drops with each damage/repair cycle.
- Hot mechanical straightening and hot working are not heat straightening; hot working should not be used on structural steel.

References

1. FHWA, Guide for Heat-Straightening of Damaged Steel Bridge Members, FHWA-IF-08-999, 2008
2. FHWA, Bridge Inspector's Reference Manual (BIRM), FHWA-NHI-12-049, 2012 (as revised)
3. FHWA, Guide for Heat-Straightening of Damaged Steel Bridge Members: Final Draft of the AASHTO Guidelines, FHWA-IF-08-999, R. R. Avent, August 2008 (rosap.ntl.bts.gov/view/dot/51757)
4. FHWA, Manual for Heat Straightening, Heat Curving and Cold Bending of Bridge Components, FHWA-HIF-23-003, F. Geoghegan, R. Medlock, B. Packard, March 2023 (fhwa.dot.gov/bridge/pubs/hif23003.pdf)
5. AASHTO/AWS D1.5 Bridge Welding Code, heat-straightening temperature limits as quoted in FHWA-IF-08-999 (1996 edition) and FHWA-HIF-23-003 (2015 edition)

Study text only; the final quiz is taken online. Verify all references against the edition your agency has adopted.