Determination of Heat-Straightening Parameters for Repair of Steel Pedestrian Bridge

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Repair of damaged steel bridges by oversized vehicles is one of the most common problems for maintenance personnel. The application of the thermomechanical method of repair to a pedestrian bridge in Warsaw, Poland, over one of the busiest expressways is presented. The comparison of three kinds of straightening is shown. The thermomechanical procedure was the most effective, but it needs still more theoretical and experimental research.

The deformation of bridges results from the impact of oversized vehicles, fire, and earthquake. Deformations are removed using methods that can be grouped into three categories: thermal, mechanical, and thermomechanical. Experienced personnel in the steel fabrication industry, construction companies, and maintenance operations know which straightening method is appropriate for a given type of deformation. This knowledge is obtained from experience and as such is not often shared. Therefore, it is useful to publish successful procedures for removing the most common deformations. The repair of a damaged pedestrian bridge is described. This type of structure is popular in many cities in Poland, and damage from the impact of an oversized vehicle occurs often.

Choosing the most economical and effective method of repair was, as always, a basic problem. It was also required that traffic continue on the road under the bridge while the heat-straightening repairs were made.

A computer simulation of various kinds of heating with or without the aid of external forces was done. Computer programs based on the method of finite differences (FDM) and of finite elements (FEM) were used for this purpose (*1*,*2*).

FDM was used to calculate the time-dependent temperature distribution in the I-beam heated by line, rectangular, and V-patterns. FEM was used for thermoplastic analysis of the steel structure.

SPECIFIC PROBLEM

The pedestrian bridge crosses one of the busiest expressways in Warsaw (Figure 1). The structure consists of two statically determinate frames joined by a simply supported beam. The frames are connected by cross beams. A noncomposite concrete slab is placed on the steel structure, which is of steel type St3M (A-36).

In one of the frames, the web of the spandrel beam was damaged by the impact of the oversized vehicle. Only the web was deformed. The bottom flange remained perpendicular to the web (Figure 1). The area of permanent deformation covered two-thirds of the length of the beam. The maximum deformation was

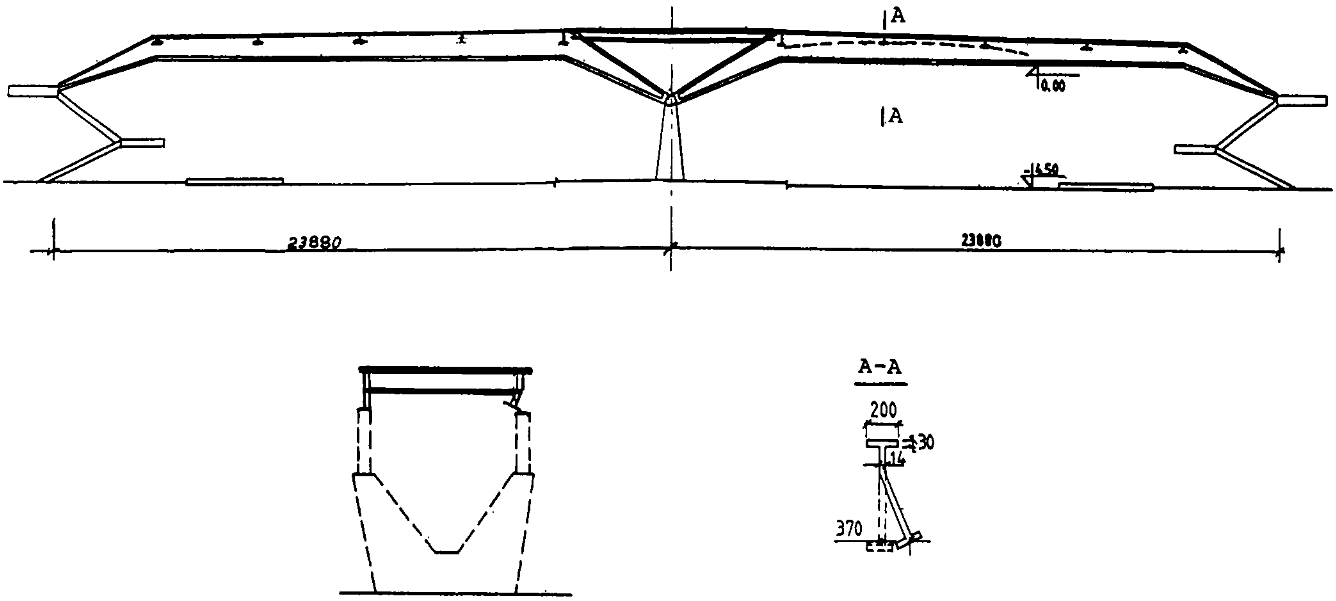

FIGURE 1 General view of pedestrian bridge.

370 mm. There were no sharp indentations, cracks, dents, or nicks.

Because of traffic congestion on the expressway, it was necessary to use a repair technique that would not disturb the activities of the city too much. Under these circumstances, it was decided to repair the damaged girder using the thermal or the thermomechanical method. It was assumed that the whole repair process would be completed over three weekend nights.

Because of a lack of experience in such repair procedures in Poland and little information from publications related to similarly damaged girders (*3–16*), it was necessary to perform more detailed theoretical and experimental analysis.

COMPUTER ANALYSIS

A series of time-independent temperature distributions generated from the heat flow analysis and, in one case, mechanical external forces were used as load steps for a nonlinear finite element analysis that produced strains, displacements, and stresses (*17,18*).

For this case, it was very difficult to assume an initial temperature distribution. Therefore, a transient analysis was used to produce a direct step-by-step solution. A 15-sec time step size was selected initially to ensure a stable solution (*18*). To simulate the heating and subsequent cooling process, a number of temperature profiles were selected so that incremental temperature change would not be too large (less than 100°C).

Nonlinearity was simulated through yielding of steel to obtain its temperature-dependent properties such as elastic modulus, yield stress, and coefficient of thermal expansion. The strains are assumed to develop instantaneously, that is, independent of time. The elastoplastic response of the steel was determined from the flow rule, yield criterion, and hardening rule.

Since the analysis is limited to a study of the plastic behavior of I-beams subjected to bending stresses, the assumption that the stresses through the cross section are nearly uniaxial is acceptable. Figure 2 illustrates the stress-strain curve for mild steel accounting for strain hardening. The Prandtl-Reuss flow rule combined with isotropic strain hardening can be used. Yielding of steel is based on the von Mises yield criterion. The flow and hardening rules are well-documented and have been applied to similar problems (*1,9,12,18*).

At first only the thermal method was considered. Three combinations of pure heating were tested. Case 1 checked the effectiveness of line heating along the deformation limit line combined with a system of V-patterns applied to the bottom flange of the beam (Figure 3). It was assumed that the line heating is made during heating of one pair of V-patterns. Two operators perform the line heating, moving from the center of the deformation limit line to the end, and the V-patterns are also made by two operators in the sequence shown in Figure 3. For analysis, the bottom flange and a portion of the I-beam were treated like a T-beam.

Five pairs of V-patterns were applied simultaneously with different spacings (average 700 mm), as shown in Figure 3. It was assumed that the temperature in the V-pattern exactly underneath the torch would be 650°C. The depth and width of the V-pattern were equal to 100

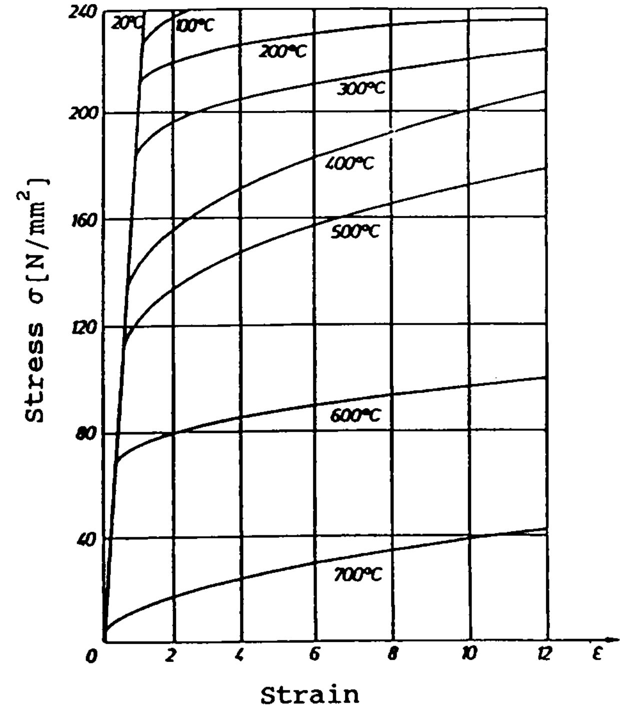

FIGURE 2 Stress-strain relation as function of temperature.

mm. For Case 1 the computed values of deformations were smaller than those required. Since the actual total deformation was about 5 mm, the maximum value of permanent deformation after heating was 1 mm.

Case 2 checked heating of the web of the I-beam by a system of V-patterns that were followed immediately by rectangular patterns on the bottom flange located directly underneath them (Figure 4). Several trials were made using groups of three, four, five, and six V-patterns with different spacings (150 and 120 cm). It was assumed that the maximum temperature under the torch was 650°C.

The depth of V-pattern was equal to the distance from the deformation limit line of the web to the bottom flange (from 400 to 600 mm). Two widths of V-pattern were assumed to be equal to its depth or three-fourths of its depth. The length of the rectangle on the bottom flange was equal to the width of the V-pattern heat. The width of the rectangle was equal to the width of the bottom flange.

The results were better than those for Case 1. The maximum total actual deformation was 6 to 7 mm, and the permanent heat-induced deformation was only 1.5 to 2 mm after one heating. Heat action would not be sufficient to restore the girder to its original shape.

Therefore, it was decided to consider Case 3 to accelerate the process. The beam was heated similarly to Case 2. V-patterns were done on the web and followed immediately by heating rectangular portions of the bottom flange directly under V-patterns.

Simultaneous to the heating, three pairs of external forces (producing a bending moment) were introduced. Force values of 3, 5, and 10 kN with a moment arm of 4000 mm were used. The points of application of the forces were located between two V-patterns (Figure 5).

The results of the analysis of Case 3 determined the preliminary parameters required in the heat-mechanical staightening procedure. They were as follows:

- Width of single V-pattern: 400 mm;
- Depth of single V-pattern: 450 to 600 mm;

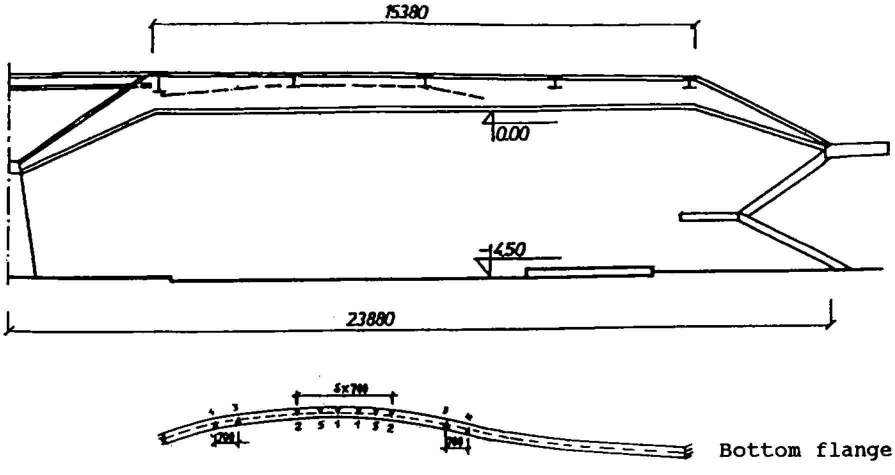

FIGURE 3 Case 1: removal of deformations.

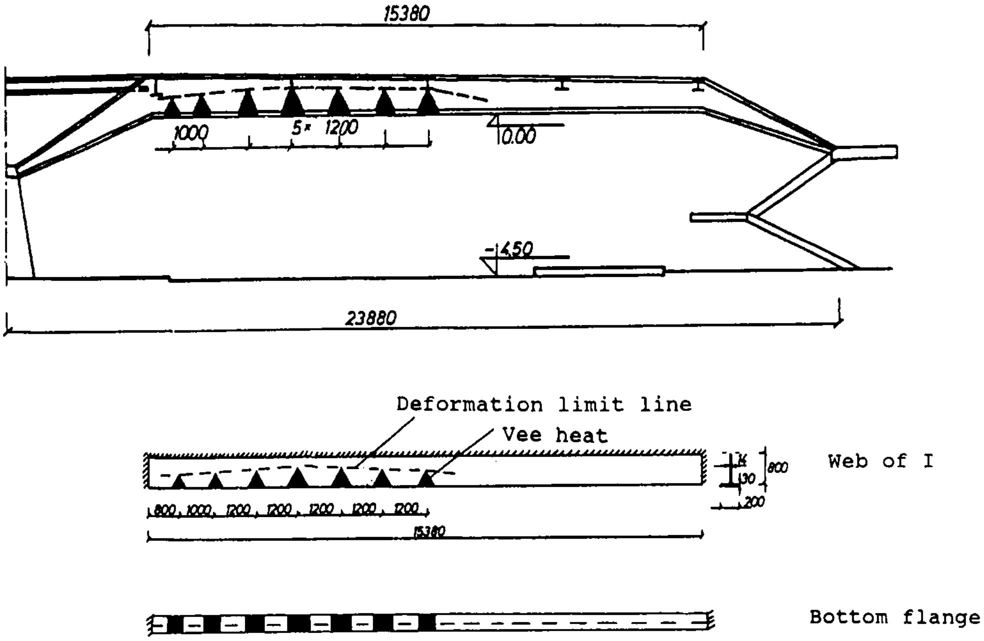

FIGURE 4 Case 2: removal of deformations.

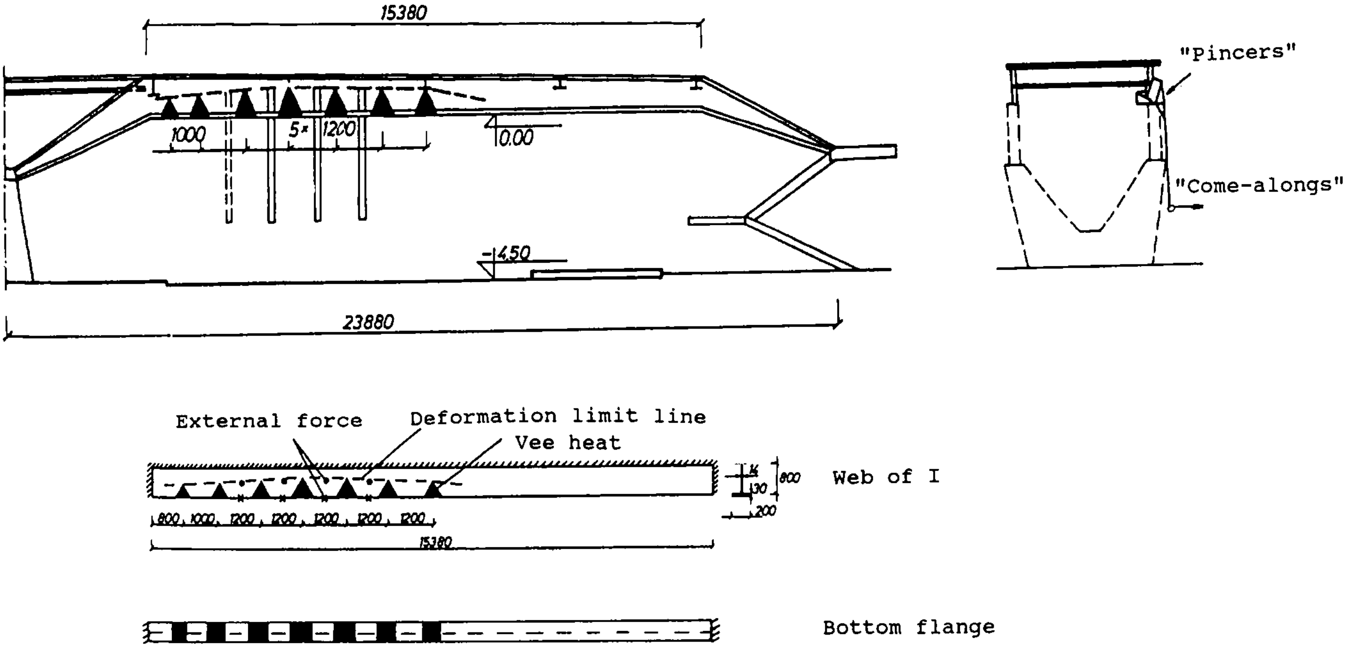

FIGURE 5 Case 3: removal of deformations.

- Spacing of V-pattern: three of their widths, or 1200 mm; and
- Value of one external force: 3 kN.

It was expected that deformations of 90 to 100 mm would be removed during one cycle. Considering the magnitude and values of the deformation, it was decided to apply three or four cycles of combined heating and mechanical action.

For all loading cases it was assumed that the temperature of the steel would not exceed 723°C. This temperature limit will prevent burn-through of the steel and change in the microcrystalline structure.

FIELD REPAIR OPERATIONS

Field repair operations were organized with the cooperation of the team from the Road and Bridge Research Institute, Warsaw, Poland, led by M. Lagoda (*19*).

The temperature on the surface of the web was measured continuously using thermal detectors. Values of external forces and deformations of the whole structure were also measured. Computer simulation determined the application of simultaneously applied V- and rectangular heats and external forces. The external forces were applied using specially designed pincers (Figure 5), which were pulled by "come-alongs" attached to a heavy truck.

Pure heating using combined V- and rectangular patterns (Case 2) gave a maximum total deformation of 6 mm but only a permanent deformation of 1.5 mm after cooling. This initial trial was not enough to complete the repair, but it compared well with the results of the theoretical analysis.

Next, the thermomechanical method (Case 3) was applied. The number of V's on the web and rectangles on the bottom flange were changed from two groups of three to one group of six done simultaneously. The spacing of the heat patterns was reduced to about 100 cm. The number of pincers was increased from three to five. Theoretically predicted values of external forces were too small, failing some pincers, which were replaced the next day with ones that could accommodate forces in the range of 4.5 to 5 kN.

The main straightening operation was performed during the second night. Three cycles of simultaneous heating and mechanical bending of the web were completed. Each lasted about 40 min, and there was a 1-hr break between cycles. Six operators were required to heat simultaneously the six V-patterns on the web and immediately heat the rectangular parts of bottom flange located directly under the V's. Three more operators pulled come-alongs at the same time, and another three operators distended both flanges of the girder by using three hydraulic jacks. The jacks were placed opposite the heated side of the web. All six V-patterns were peened immediately after each heating-bending cycle was finished. One V-heat and one pincer were transferred from the right to the left side of the web during the third cycle.

Heat was applied as follows: the V-patterns were placed on the external side of the web, to cause shrinking. The heat path in each pattern was kept as close as possible. The speed of the torch was to be 15 cm/min, which was dependent on the operator's skill. The distance between the steel plates and torch head was to be about 8 mm, but it was practically impossible to control that parameter. Continuous control of steel temperature was good. The temperature of 723°C was exceeded only twice for periods not longer than 15 sec. The value of external forces in the come-alongs was checked using ordinary dynamometers.

The deformations in secondary components of the bridge were cleaned up and removed during the third night. Finally, the whole structure was cleaned and painted.

Results of the repair given in Table 1 confirm that the thermomechanical method of straightening is effective from the technical as well as the economical point of view. The deformations are sufficiently large and were straightened in a relatively short time. The permanent deformation of the web in Section A-A (Figure 1) was 366.5 mm, and it was straightened almost completely.

Unfortunately, some local deformations remained in the girder. They are located mainly along the deformation limit line in the web. One local buckle still exists in the bottom flange, where it was hit by the truck. These deformations do not exceed 20 mm and can be removed later by the pure heating method.

It is possible to control most of the technological parameters of the process with sufficient accuracy by carefully monitoring the steel temperatures at the locations where the heat is applied as well as stresses at selected points in the structure.

CONCLUSIONS

The following conclusions can be drawn from the thermomechanical heat-straightening procedures described:

1. Pure heating works only when deformations are small. The limits can be determined from computer simulations and in practice.
2. For large deformations it is necessary to combine both heating and mechanical force to straighten members.
3. It is easier to remove large deformations than smaller ones. Smaller deformations require more precise

TABLE 1 Deformation After Heat Straightening

Number of cycle	Total deformation (mm)	Permanent deformation (mm)
I night (heating only)	6	1.5
II night (heating and "pincers")		
1 cycle	120	45.0
2 cycle	250	140.0
3 cycle	330	180.0
		Σ = 366.5

effort and more time and should be done only by skilled and experienced technicians.

4. Torch operators never work in the same manner. Therefore, it is necessary that they be taught how to apply heat patterns to the structure, which is a different skill than welding. The most important rule is to keep the torch at a constant distance from the heated surface and to move it with a constant velocity.

5. Field modification of theoretically designed thermomechanical repairs is always needed. Determination of temperature distribution, real values of modulus of elasticity, yield stress, and coefficient of thermal expansion at elevated temperature are still unknown parameters.

6. It is essential to determine a force and temperature distribution in the structure and to know which part will be plastified and what the corresponding temperature will be. For future life of the structure, it is important to predict which part remains plastified and whether this is dangerous. As assumed in Cases 2 and 3, the statical scheme of the structure under consideration was not appropriate because of difficulties in determining the real restrain from the concrete slab.

7. There is a need to correct calculation techniques and selection of heating parameters in regard to dimensions and spacing of the V-patterns. Those given in the literature conflict and relate mostly to small elements tested only in the laboratory. The techniques given by Baldwin and Guell and by Brockenbrough (*5–8*) are for heat curving, but they proved to be realistic.

8. The observations made during this operation suggest that the depth of the V-heat should be about two-thirds to three-fourths of the steel plate (web or flange) width (depth) or that it must cover the depth of the web deformations. The width of the V-pattern should be about three-fourths of its depth. The estimated spacing of V-patterns needs more research and field verification: according to these observations, it could be two to three widths of the V-heat.

9. The behavior of steel structures in elevated temperatures—that is, in the plastic state—is not always predictable, and the results of theoretical calculations differ greatly from practice.

10. It is more economical to repair structures than to replace them, as shown by the repair techniques described.

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