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Projects 12-1 and 12-6 FY '65 and '67

Permanent Deflections and Loss of Camber in Steel Bridge Beams

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Introduction and Research Approach

Description of the Problem

Observations of bridges in the AASHO Road Test indicated that permanent deformations and loss of camber occurred in the steel beams even when the stress level computed from measured strain was below the known yield point of the steel. This finding raised a question as to what stresses, in addition to those caused by loading, were present in the beams so that the total stress exceeded the yield point. Furthermore, there are questions as to what extent similar conditions exist in typical highway bridges and whether they are significantly influenced by the choice of a cambering method.

Objective and Scope

The findings presented in this report are the results of two research projects: Project 12-1, "Deformation of Steel Beams Related to Permitted Highway Bridge Overloads," and Project 12-6, "Prediction of Permanent Camber of Bridges."

The complete documentation of the research is contained in Appendices II through V of the agency report, which are not published herein. The appendices are available from University Microfilms.* The material for Project 12-1 is documented in Appendix II, "Permanent Deflections in Highway Bridge Beams." Project 12-6 research is documented in Appendix III, "Effect of Cambering Method on Loss of Camber in Wide-Flange Steel Beams; Appendix IV, "Flame Cambering of Wide-Flange Steel Beams; and Appendix V, "Temperature Prediction in Flame Cambering of Wide-Flange Steel Beams."

The scope of both projects included:

1. A survey of available field data concerning evidence of permanent deformations in existing highway bridges.
2. A survey of available data on residual stresses in rolled beams.
3. A survey of existing practices for cambering beams and a categorization of cambering methods.
4. For composite construction, the determination of the effects of slip in the shear connection, shrinkage of the concrete slab, and creep in the concrete slab.
5. The determination of the magnitude and distribution of residual stresses, and the variation of yield point in steel beams as rolled and delivered to the fabricator without camber.
6. The determination of the effect of certain cambering methods on residual stresses.
7. The determination of permanent deformation in steel beams, with and without camber, subjected to repeated loads of various levels lower than those causing computed yield point stress. The number of cycles of load applied was to approximate six months of service load on a bridge.
8. The development of a method of analysis to predict the permanent deformation of steel beams.

Project 12-1 included analytical and experimental studies of one as-received and one cold-cambered noncomposite 27 WF 94 beam 36 ft in length and one concrete-on-steel composite beam 36 ft in length.

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Project 12-6 involved analytical and experimental studies of noncomposite beams in the as-received condition as well as beams cambered by four different methods—cold cambering and three methods of flame cambering. The flame-cambering methods are referred to as continuous heating, wedge heating, and spot heating. Two different beam sections (27 WF 94 and 27 WF 160) were examined. These shapes were selected because they are representative of beams used in highway bridges and they present a wide difference in flange thickness. Beams were coded according to size and method of cambering as given in Table 1.

TABLE 1

TEST BEAM DESIGNATIONS

BEAM		
27WF160	27WF94	DESCRIPTION
AC1	BC1	Cold cambered and used for residual stress and yield point determination
AC2	BC2	Loaded as received, cold cambered, and reloaded
AF1	BF1	Flame cambered by continuous heating and loaded
AF2	BF2	Flame cambered by wedge heating and loaded
AF3	BF3	Flame cambered by spot heating and loaded

Experimental Study

Residual Stresses and Yield Point.—The initial step in the experimental work was to determine the residual stress and yield point distributions in test beams as they were received from the mill. Because these determinations are destructive in nature, distributions obtained for each beam size were assumed to exist for all beams of a single size and heat of steel. Residual stresses and yield point were also determined after cambering and again after load testing.

Static Test Series, Project 12-1.—Three beams were tested under static loading. The first test incorporated only the study of permanent deflections in noncomposite beams resulting from a combination of loading stresses and residual stresses as received from the mill. This phase included testing a 27 WF 94 steel beam 36 ft in length. The test procedure also served as a method of cold bending the beam for later testing.

The second test included consideration of residual stresses resulting from cold bending during fabrication. This test was accomplished by reverse loading the same 27 WF 94 beam that had been subjected to controlled cold bending during the first-phase test.

Effects of residual stresses on permanent deflections in composite beams were considered in a third test. A 36-ft composite section, which consisted of the 27 WF 94 steel beam employed in the first and second phases and a 6-in. by 60-in. concrete slab, was tested.

Cambering, Project 12-6.—All beams used for cambering and repeated-load testing for Project 12-6 were 36 ft long and were simply supported during both operations. In addition to these beams, each of the flame-cambered beams was accompanied by a 9-ft-long companion segment. These segments were cambered by the various methods and used to determine the residual stresses produced by the cambering technique.

Each long beam was instrumented to determine curvature and deflection during cambering. The flame-cambered beams were also wired with thermocouples to record temperature history during and after heating.

Mechanical Cambering.—The beams were cold cambered by simply supporting them at the ends and jacking against them with hydraulic rams. The two rams were spaced 5 ft 11 in. apart and positioned symmetrically about midspan.

Flame Cambering.—For the flame-cambering tests, care was taken to duplicate as nearly as possible the conditions found in practice. Continuous-heating equipment was borrowed from a fabricating shop for use in the laboratory. Instructions related to torch size and speed and gas pressure were obtained from the shop foreman. Cambering both by wedge heating and by spot heating was carried out in the laboratory by an experienced industry technician, whose specialty was flame cambering by those particular methods.

For the continuous-heating method of flame cambering, three torches were mounted on a motor-driven carriage that traveled on the top flange. The torches were spaced to apply heat to the entire flange width and each beam was heated over its entire length. The average speed was 12 in. per minute for AF1 and 16 in. per minute for BF1. Temperature-indicating crayons and thermocouples indicated that the surface temperature of the steel reached approximately 1,200 F.

For wedge heating, five sections along the length of each beam were heated. At each section a wedge-shaped area of the web was heated first, with the apex of the wedge at the bottom flange. After a short pause (approximately 3 min) to allow cooling, a rectangular area on the top flange directly over the wedge was heated. The area was approximately 5 in. long and covered the full width of the flange. Approximate heating times at each section were 6 min for the web area and 7 min for the flange. Temperature-indicating crayons showed that the surface of the flange remained above 1,200 F for as long as 7 min after heating had stopped. It was estimated (by the color of the steel) that the temperature was as high as 1,700 F.

Again for spot heating, five sections along the length of each beam were heated. At each section a rectangular area approximately 3 in. wide by 16 in. long on the top flange directly over the web was heated first. The width of this area did not cover the full flange width but was limited to about 3 in. Immediately after the flange was heated, a triangular area of the web was heated. This area was approximately 10 in. in both length and depth. Maximum temperatures were approximately the same as those for wedge heating.

Repeated-Load Tests.—The load tests for Project 12-6 were repeated applications of design load and allowable overload. (Section 1.2.4 of AASHTO's *Standard Specification for Highway Bridges* specifies the allowable overload stress to be 150 percent of design load stress, which is 20,000 psi.). All load tests were conducted at 0.25 cycles per second using two hydraulic rams applied at the third points of the beam. During load tests, instrumentation on the beams measured beam load, deflection, curvature, and strain.

Beams AC2 and BC2 were first load tested as received; they were then cold cambered and load tested again. The test sequence was to apply:

1. Successively increasing increments of load to design load.
2. Approximately 200 cycles of design load.
3. Successively increasing increments of load to attain 1 cycle of allowable overload.
4. Approximately 20,000 cycles of design load.
5. Approximately 1,000 cycles of overload.

During steps 1 and 3, the beam was held at each load level to allow the deflection to stabilize. Because time was allowed for complete yielding during step 1, no additional loss of camber occurred during step 2. Similarly, no additional loss of camber occurred during steps 4 and 5 once 3 had been completed. Because of the desire to observe the effect of the repeated loading, the aforementioned loading sequence was altered for the remaining beams. The new sequence adopted was 2, 1, 4, 5, and 3.

Theoretical Analyses

One of the objectives of the research reported herein was to develop a rational method of analysis in order to predict the behavior of beams, both noncomposite and composite, uncambered and cambered. To achieve this objective, three theoretical analyses were developed. In order of their application to the cambering problem, they are:

1. "Temperature Prediction in Flame Cambering of Wide-Flange Steel Beams." A computer program was developed to predict the temperature field, as a function of time, in a beam during flame cambering.
2. "Flame Cambering of Wide-Flange Steel Beams." A computer program was developed to determine the induced curvature and stresses due to a given temperature history.
3. "Permanent Deflections Resulting From Residual Stresses." A computer program was developed to predict permanent deflection or loss of camber resulting from known residual stresses and a given loading.

The results of the first program were used as input to the second in order to predict residual curvature and stresses resulting from each method of flame cambering described earlier. The residual stresses thus obtained were used in the third program to determine loss of camber. In the case of uncambered beams, only the third program is needed. Because this program uses residual stresses as input, either theoretically or experimentally determined residual stresses can be used. A rather complicated combination of programs, described in Appendix II, was used in the analysis of the composite beam.

TABLE 2

COMPOSITE BEAM ANALYSIS

FACTOR	CASE 1	2	3	4	5
Initial stress	No	Yes	Yes	Yes	Yes
Slip	No	No	Yes	Yes	Yes
Strain softening (%)	No	No	No	10	50
Total midspan deflection at design loan (in.)	0.50	0.50	0.50	0.52	0.60
Permanent midspan deflection at design load (in.)	0.00	0.00	0.00	0.02	0.09
Total midspan deflection at nominal yield (in.)	0.97	1.03	1.08	1.14	1.30
Permanent midspan deflection at nominal yield (in.)	0.00	0.06	0.11	0.17	0.33

Findings

Permanent Deflections

Test Results, Project 12-1.—Measured residual stress and yield point distributions for the steel beam in the as-received condition are shown in Figures 1 and 2. Computed initial stresses in the composite test beam are presented in Figure 3.

Both experimental and predicted results for moment versus curvature and load versus deflection for the phase-one test are shown in Figures 4 and 5. Good agreement between the experimental and predicted values is observed.

Results of load versus deflection and permanent deflection for the phase-two test are shown in Figure 6. When both residual stresses and the Bauschinger effect are accounted for, the comparison between theoretical and experimental results is very good.

For the composite phase-three test, five theoretical cases were considered. These cases involved various degrees of composite action, initial stress, and strain softening as given in Table 2. The results of moment versus curvature and load versus deflection are shown in Figures 7 and 8. The agreement between the predicted (case 5) and measured deflections is excellent up to a load approximately 15 percent greater than the nominal yield load. Above this load, the measured deflection was less than the predicted value. During this loading, the bottom fibers of the steel beam were subjected to strains in excess of the yield strain for the third time. Although this may have caused some strain hardening in these fibers, it is also quite possible that the discrepancy between predicted and observed values was the

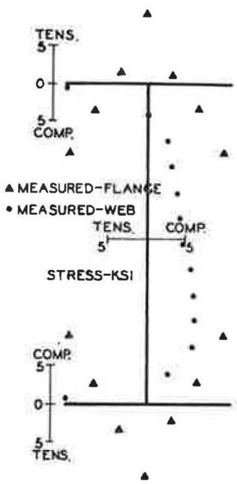


Figure 1. Residual stresses for the as-received test beam.

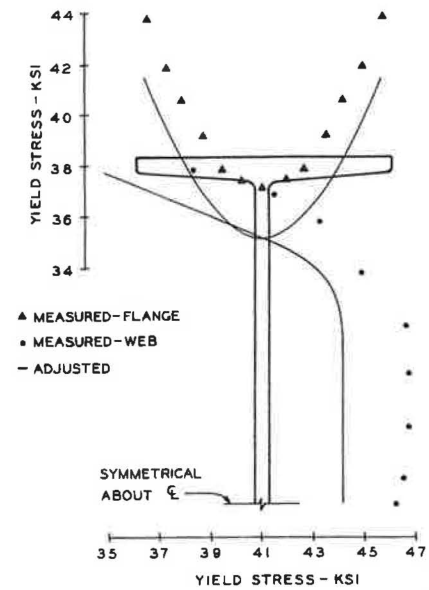


Figure 2. Yield point distribution for the as-received test beam.

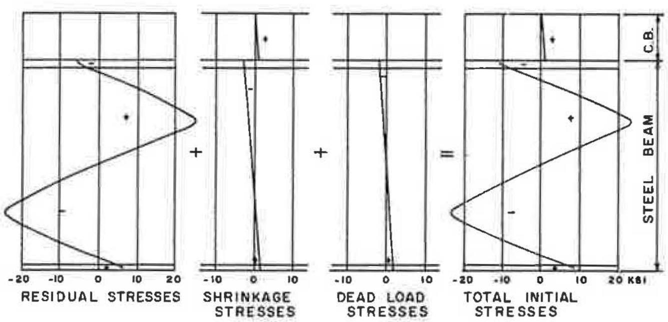


Figure 3. Computed initial stresses in composite test beam.

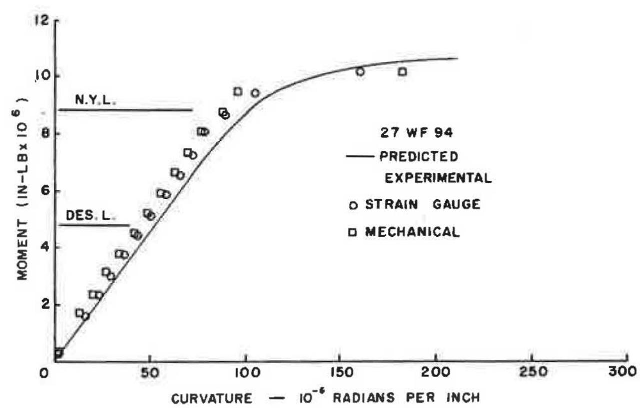


Figure 4. Moment vs curvature in the as-received test beam.

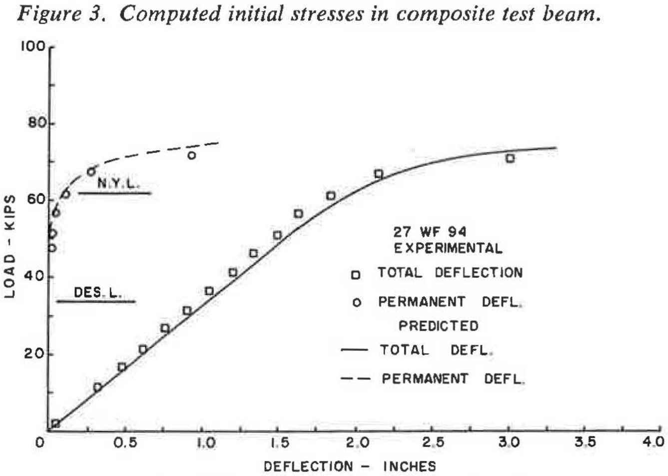


Figure 5. Load vs deflection in the as-received test beam.

result of assuming a strain softening ratio * of 50 percent for all fibers in the steel beams when the upper two-thirds of the beam were not actually being subjected to reversed yielding.

A plot of load versus permanent deflection is shown in Figure 9. Again, agreement between predicted (case 5) and measured deflection is quite good up to loads approximately 15 percent greater than nominal yield load.

* A detailed description of the strain softening ratio is given in Chapter II of Appendix II.

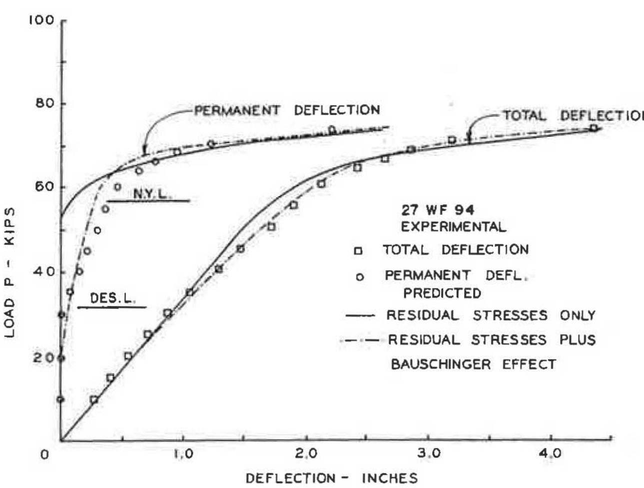


Figure 6. Load vs deflection in the cold-bent test beam.

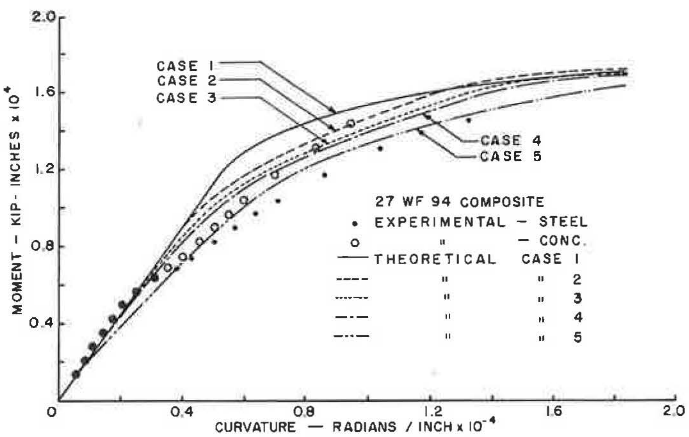


Figure 7. Load vs midspan curvature in the composite test beam.

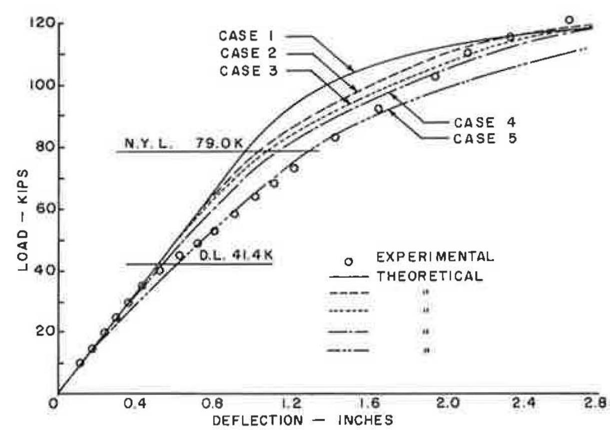


Figure 8. Load vs midspan deflection in the composite test beam.

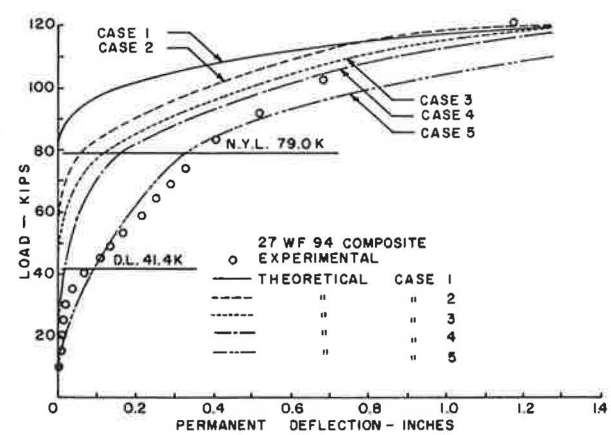


Figure 9. Load vs midspan permanent deflection in the composite test beam.

Figures 8 and 9 allow a comparison of the contributions of slip, residual stress, and strain softening. Table 2 also gives this comparison in tabular form. These comparisons make it clear that, up to nominal yield load, the elastic action is by far the largest contributor to total deflection with strain softening, residual stresses, and slip following in descending order of importance. Permanent deflection remaining after removal of the nominal yield load was approximately 34 percent of the elastic deflection under nominal yield load. Even though the test beam had substantially fewer shear connectors than required by the 1965 AASHO code, slip contributed very little to the permanent deflection.

Field Studies.—In an effort to obtain field data to which the results of the laboratory study could be compared, a questionnaire was sent to state and province bridge officials in the United States and Canada; city engineers or planners for cities in the United States having a population of 250,000 or over; members of the AASHTO operating subcommittee on bridges and structures; and bridge engineers for the major railroads in the United States and Canada. The initial questionnaire was a simple business-reply card with a place for the respondent to check whether or not his department had data concerning permanent deflections in bridge stringers and whether they would be willing to furnish this information. Of the 190 questionnaires mailed, 90 were returned. Of these, only 15 replies were affirmative. Follow-up of these 15 replies produced only two useful sources of information.

One source of information was an agreement with the Highway Division, Department of Transportation of the State of Hawaii, to instrument a bridge under construction and to follow-up measurements for a period of 6 months after the bridge was open to traffic. The other source of information was the California Division of Highways, which furnished data on 12 bridges. Data related primarily to slab shrinkage and agreed quite well with predicted values.

Effects of Cambering

Survey of Cambering Methods.—The original research plan for Project 12-6 called for a questionnaire in order to determine the method of cambering most commonly used by producers and the major fabricators. However, initial site visits and telephone inquiries revealed little if any standardization of flame-cambering methods. It seems that each shop foreman and each iron worker has his own special technique and his own set of terms to describe the process. Therefore, the development of a simple survey questionnaire was not feasible. However, discussions with a number of individuals who practice flame cambering revealed that most techniques are derived from combinations or variations of the three basic processes referred to herein as continuous heating, wedge heating, and spot heating.

Site visits revealed a low degree of quality control in current practices. For example, although cold cambering of beams is a rather simple process that is easily described, cold-cambered beams exhibit considerable variation in amount of camber. In addition, some beams become over-cambered and, subsequently, are reverse loaded to reduce the over-camber; others are deformed only once. As a result, adjacent beams in a bridge can exhibit greatly different properties in regard to loss of camber.

Yield Point and Residual Stress, Project 12-6.—Typical as-received yield point variations are shown in Figure 10. Table 3 summarizes the results of the yield point determinations before and after cambering. Although the cambered AC1 beam exhibits a somewhat higher yield point than the as-received beam, Table 3 does not indicate any other significant change in yield point resulting from any of the cambering methods investigated.

Results of the as-received residual stress determinations for the two beam sizes are shown in Figure 11. Some representative plots of experimental and theoretical residual stresses resulting from cambering of the Project 12-6 beams are shown in Figures 12 and 13. It was found that all four methods of cambering produced undesirable tensile residual stresses in at least part of the flange that carries tension under service conditions. Residual stress patterns varied considerably depending on the cambering method used and, in some cases, substantial discrepancies existed between the theoretical and experimental values. Both predicted and measured residual stresses exceeded 60 percent of the yield point in at least one location in all flame-cambered beams.

Part of the discrepancy between experimental and predicted results is attributed to the failure of the analysis to correctly predict the complete temperature-time relationship of every beam fiber during both heating and cooling. The residual stress field induced by heat is very sensitive not only to the maximum temperature but also to the temperature-time relationship for every beam fiber during both heating and cooling.

In predicting the temperature-time relationship for the wedge-heating technique, the flange heating pattern was simulated as a uniform heat flux applied over the top flange. This pattern did not yield good residual stress predictions. Subsequent examination of the moving pictures filmed during cambering indicated that there was a significantly different heating pattern. Thus the simulation was not valid, and large discrepancies are to be expected. The actual heating sequence was so complex and so dependent on visual feedback to the operator that it was impossible to model accurately.

Another factor that affected the accuracy of the predicted residual stresses was the assumption that plane sections before heating remain plane during heating and after cooling. Figure 14 shows typical plots of the average-strain distributions for three of the beams. Examination of the graphs shows that the assumption was good for continuous heating, fair but not completely correct for wedge heating, and considerably in error for spot heating.

In the cases of spot heating and wedge heating, the accuracy of observed residual stresses was also affected by the highly localized nature of the heating. The experimental residual stresses shown in Figures 12 and 13 were determined from strains measured over a 10-in. gauge length and represent the average residual stress over that length. In cases where only a part of this length was heated, it is highly likely that the maximum stress was considerably higher than the average.

The residual stress distribution remaining after completion of the loading sequence was experimentally determined for all beams except BC2, which was badly deformed by a malfunctioning ram. Predictions were made for the residual stresses after loading based on both the measured camber-induced residual stresses and the calculated camber-induced residual stresses. Figure 15 gives example plots showing comparisons of the experimental and predicted residual stresses with the beam oriented in the loading position (reversed from the cambering position).

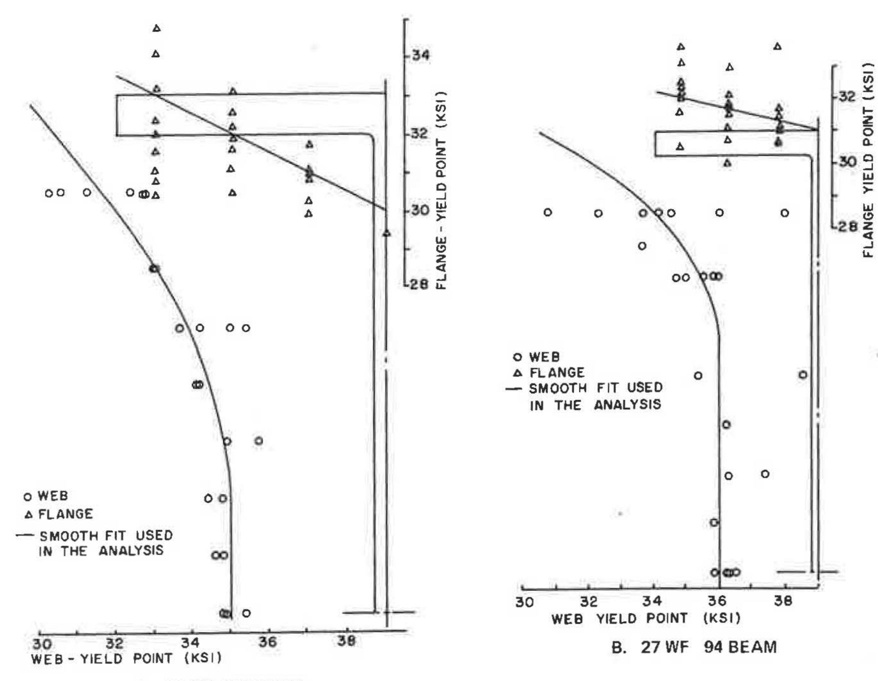


Figure 10. Yield point distributions for as-received test beams.

Camber and Loss of Camber, Project 12-6.—Experimental and predicted results for the camber are given in Table 4. The use of a deflection control method for cold-cambering beams in the laboratory resulted in good agreement between experimental and predicted values of camber for beams AC2 and BC2. The accuracy of the predicted camber for the flame-cambered beams was, in general, not as good as for cold cambering. Differences occurring between the wedge- and spot-heated beams are believed to be due to the difficulty in accurately modeling the heating process for these techniques of flame cambering. Also involved is the determination of the exact effective length of the heated zone.

Experimental and predicted loss of camber due to design load and permitted overload are also given in Table 4. The predicted loss of camber was determined using both experimental and theoretically predicted residual stresses resulting from cambering. A typical graph of the loss of camber with cycles of design load and overload is shown in Figure 16. In all cases, it was found that for any load level no additional loss of camber occurred after a (static) cycle

TABLE 3

YIELD POINT STRESS[a] IN TEST BEAMS

BEAM	LOCATION (SEE DRAWING) 1	2	3	4
AC1	30.7	30.2	32.7	34.9
As Received	30.8	30.9		
	31.5	31.0		
AC1	33.1	31.8	31.3	34.8
Cambered	32.0	31.1	32.8	
	34.1	29.9		
	34.7	31.0		
AF1				
Cambered	32.4	30.4	30.6	35.4
AF2				
Cambered	30.4	29.9	30.3	—
AF3				
Cambered	31.0	30.2	32.4	—
BC1	32.3	30.7	33.6	36.5
As Received	32.0	31.5	34.1	35.9
BC1	32.4	31.1	32.3	36.2
Cambered	32.2	31.4	30.7	36.3
	31.6	31.7		
BF1				
Cambered	33.6	30.6	36.0	—
BF2				
Cambered	33.2	33.6	34.5	—
BF3				
Cambered	30.5	34.6	38.0	—

[a] In ksi.

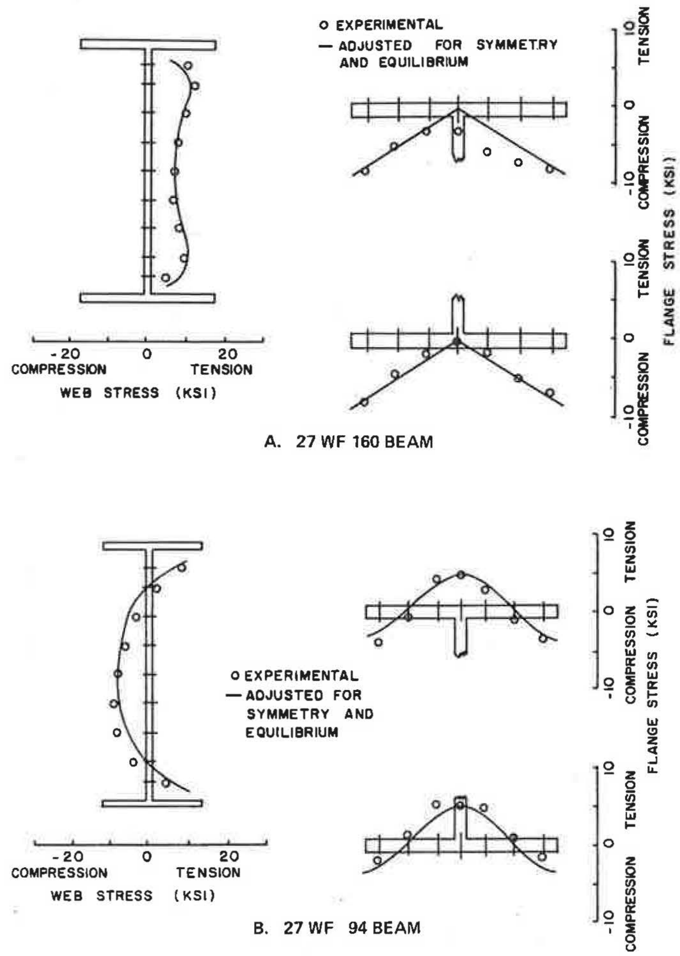
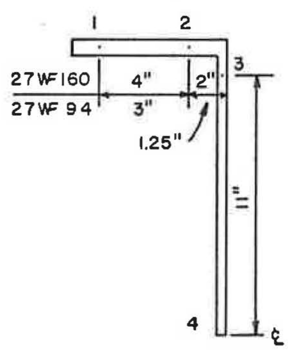


Figure 11. Residual stress for as-received test beams.



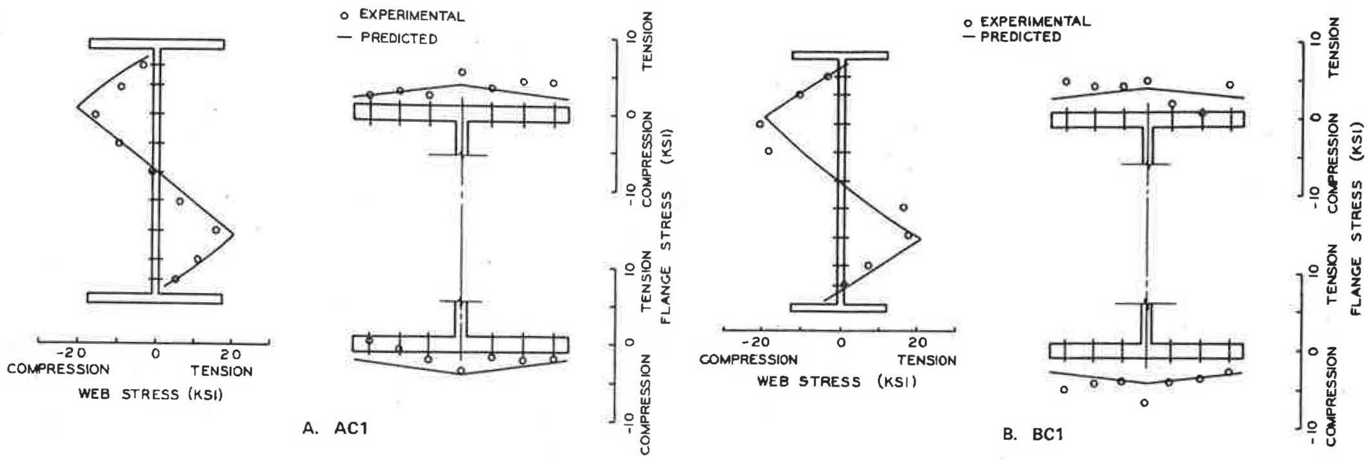
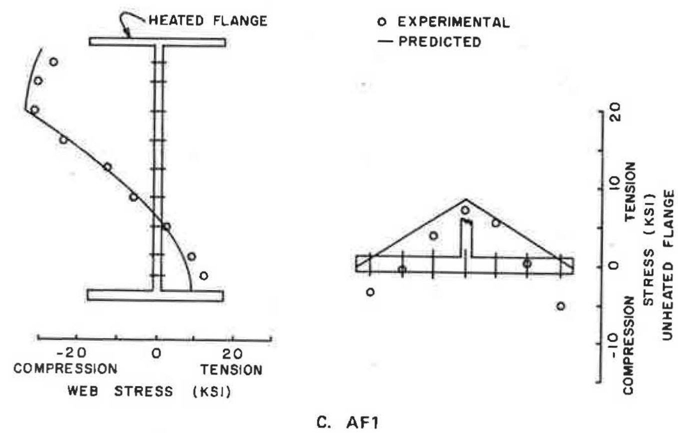


Figure 12. Residual stress in three test beams induced by cambering.



of load had been slowly applied. Loss of camber, under cyclic load, tended to stabilize at a value equal to that produced by a single slowly applied cycle of load at the same level.

As given in Table 4, the discrepancy between predicted and observed losses of camber for the as-received load test of beam AC2 may be due to an accidental overload attributable to inexperience in the operation of a newly installed cyclic loading system. Results for the cold-cambered beams AC2 and BC2 compare favorably for both the experimental and predicted residual stress distributions. Results showed that the experimentally determined curvature for

TABLE 4

LOSS OF CAMBER IN TEST BEAMS

	CAMBER (IN.)		LOSS OF CAMBER (IN.)					
					PREDICTED			
			EXPERIMENTAL		EXPERIMENTALLY DETERMINED RESIDUAL STRESSES		ANALYTICALLY DETERMINED RESIDUAL STRESSES	
BEAM	EXPERIMENTAL	PREDICTED	DESIGN LOAD	OVERLOAD	DESIGN LOAD	OVERLOAD	DESIGN LOAD	OVERLOAD
AC2 as received	—	—	0.021	0.309	0.000	0.180	—	—
AC2 cambered	1.675	1.593	0.261	0.741	0.284	0.735	0.289	0.755
AF1	1.820	1.810	0.137	0.555	0.292	0.769	0.319	0.860
AF2	1.623	1.184	0.028	0.302	0.005	0.282	0.084	0.339
AF3	1.647	0.543	0.063	0.248	0.046	0.278	0.058	0.273
BC2 as received	—	—	0.021	0.309	0.000	0.180	—	—
BC2 cambered	1.534	1.500	0.211	0.625	0.258	0.678	0.266	0.660
BF1	1.535	2.790	0.418	0.961	0.572	1.164	0.861	1.520
BF2	1.694	0.606	0.041	0.388	0.000	0.194	0.092	0.232
BF3	1.592	0.624	0.050	0.298	0.034	0.165	0.051	0.155

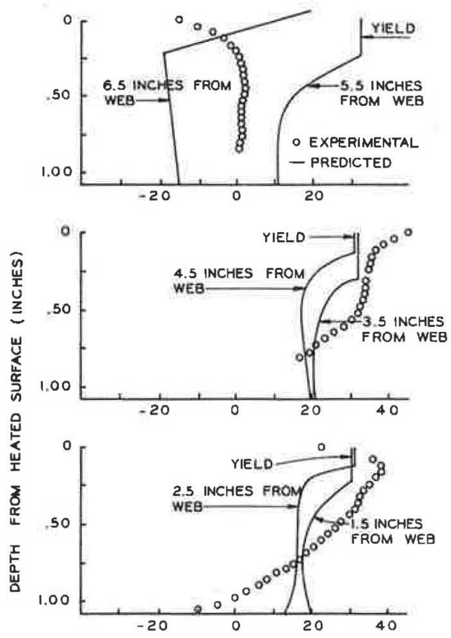


Figure 13. Residual stress induced by cambering in heated flange of beam AF1.

the companion beam segments was greater than that of the parent beam for the beams cambered by continuous heating. Thus the measured residual stresses were larger in the companion beams and the predicted loss of camber based on these measured residual stresses was greater than that observed in the test beam. Because of the wide variations in curvature at the heated regions in a beam subjected to wedge or spot heating, the experimentally determined residual stresses from the companion beam segments represented a rather crude approximation of the actual residual stresses in the parent beams. Thus, close comparisons for loss of camber were not achieved, but a relative order to the loss of camber was obtained. In all cases the losses of camber resulting from wedge and spot heating were very nearly equal, and specimens cambered by either method exhibited much lower loss of camber than those cambered by either continuous heating or cold bending.

Microstructure.—When it was realized that flange temperatures were well above the recrystallization temperature during the wedge- and spot-heating procedures, there was concern about the possibility of grain growth in the steel. A total of 24 metallographic specimens were cut, polished, etched, and photographed under a metallurgical microscope to determine grain size. Half of these specimens were cut from heated zones and half from unheated zones in the test beams.

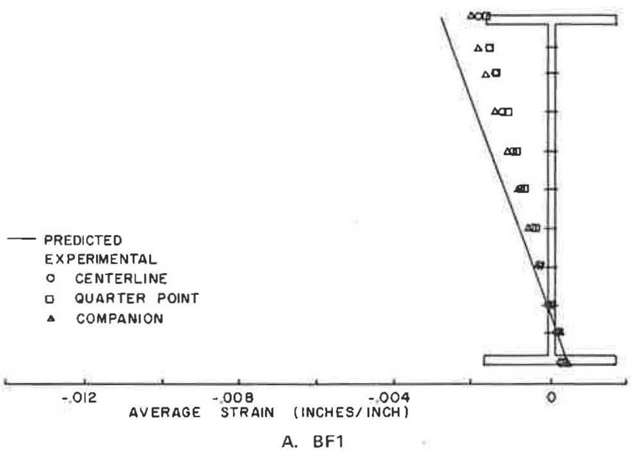
Although there was considerable random variation in the grain size, there was no indication that any of the flame-cambering methods significantly affected the grain structure of the steel. Tension tests of coupons cut from the heated zones indicated that there was also no appreciable change in the mechanical properties of the steel.

Interpretation, Appraisal, and Application

General

The findings of this study make clear that, in addition to the normally computed effects of loading, the following factors may produce permanent deflections in highway bridges:

1. Effective static yield point of material below nominal yield point.



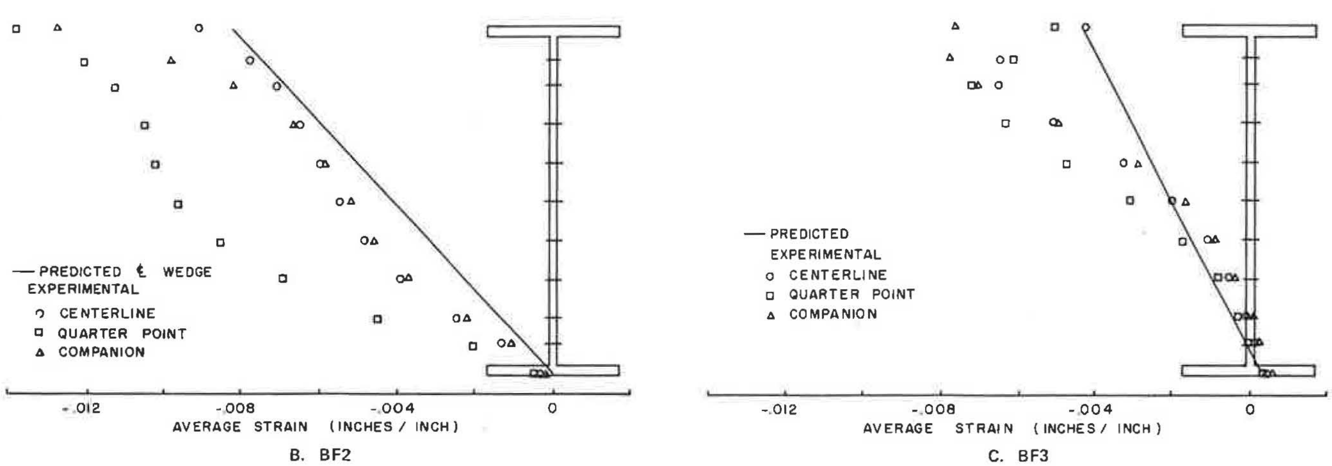


Figure 14. Average-strain distributions resulting from flame cambering.

2. Cooling residual stresses.
3. Cold-bending residual stresses.
4. Strain softening (Bauschinger effect).
5. Shrinkage of concrete deck slab.
6. Slip in the shear connection.

From a research standpoint, all of these factors can be predicted with a reasonable degree of accuracy when sufficient information is available about the fabrication history of the beam and when sufficient effort is devoted to measurement of material properties. From a practical design standpoint, however, accurate prediction of the permanent deflections resulting from these factors is very difficult. Some of the needed information simply does not exist at the time a beam is designed, and the net effect of some factors is not great enough to justify the cost of measurements and analyses. However, a knowledge of the bounds on deflections, which can be caused by various factors, combined with engineering judgment should produce estimates of permanent deflections entirely satisfactory for design purposes.

The field survey undertaken as part of this project indidates that, quantitatively, very little is known about the occurrence of permanent deflections in the field. There is doubt as to whether permanent deflection or loss of camber has been a problem in any bridges to date. During the past few years, however, there has been sufficient concern about the riding qualities of bridges that several new bridges have been instrumented and are under observation.

Effective Yield Point.—Because yielding is a time-dependent phenomenon, the effective yield point under a static or very slowly applied load is somewhat lower than that indicated by a standard tension test. In addition, there is considerable variation in the yield point of the material across the section of a beam, and the lower yield points usually occur in the flanges whereas mill test specimens are taken from the web. A combination of these factors may result in an effective flange yield point under static load being as much as 15 to 20 percent below the nominal specified yield point, particularly in beams with thick flanges. This in itself poses no particular problem so long as permitted overloads do not produce stresses greater than approximately 80 percent of the nominal yield point. Unfortunately, the highly nonlinear nature of the relationship between stress and permanent deflection causes this reduction in effective yield point to greatly magnify the deflections resulting from the Bauschinger effect.

Residual Stresses.—Residual stresses resulting from differential cooling after rolling are present in all rolled sections. Although some investigators have reported cooling residual stresses as high as 17 or 18 ksi for smaller beams, a maximum value of 10 ksi was found in the current study. It should probably be noted that measuring residual stresses in beams as received from the mill does not ensure that these residual stresses are due to cooling alone. The straightening processes used in the mill on large rolled sections induce cold-bending residual stresses, which are partially superimposed on cooling residual stresses. As a result there may be considerable variation in the residual stresses along the length of a beam. However, cold-bending residual stresses in the flanges of heavy wide-flange sections have a relatively small magnitude on the order of 5 or 6 ksi. Thus, even a combination of cooling and cold-bending residual stresses is not in itself sufficient to cause yielding at the normal design load. Even with permitted overloads the contribution to permanent deflection is relatively small.

Strain Softening.—The strain softening (Bauschinger effect) that accompanies cold bending in the mill or fabricating shop is a much more significant factor than the cold-bending residual stresses. Although the Bauschinger effect does not lower the yield point in structural steel as is sometimes implied, it does reduce the elastic limit well into the normal working-stress range. For the beam tested during Project 12-1, the permanent deflection due to a combination of cooling residual stresses, cold-bending residual stresses, and the Bauschinger effect was essentially zero at working load levels and 12 or 13 percent of the nominal elastic yield deflection following an application of permitted overload. However, the average static yield point of the flange in this beam was approximately 37.5 ksi. The permanent deflections were much higher for beams AC2 and BC2 in Project 12-6, wherein the average static flange yield points were approximately 31.5 ksi. Expressed as percentages of nominal elastic yield deflection, the permanent deflections in beams AC2 and BC2 were 15 and 12 percent, respectively, when subjected to design loads and 42 and 35 percent, respectively, when subjected to permitted overloads.

Slab Shrinkage.—All of the foregoing factors that contribute to permanent deflections in noncomposite beams also contribute to permanent deflections in composite beams. In addition, shrinkage of the concrete deck slab contributes to permanent deflections in composite beams. When known, the concrete shrinkage contribution to permanent deflection is relatively easy to calculate, but accurate predictions of shrinkage values in field-placed concrete are extremely difficult to make. Bridge deck shrinkage commonly varies from 0.0001 to 0.0003 in. per inch. Findings of this study indicate that in most cases permanent deflections resulting from deck slab shrinkage usually range from 30 to 60 percent of the elastic deflection caused by deadload of the deck.

Slip in the Shear Connection.—Slip in the shear connection contributes to the deflection of composite beams in two ways. Once the chemical bond has been broken, the shear connection is basically elastic in nature and the stiffness of the composite beam may be 10 to 15 percent less than that computed for the transformed section. Friction in the shear connection can then prevent complete recovery of the slip following removal of the load and can result in permanent deflection. However, when a shear connection includes sufficient connectors to fully develop the strength of the beam, permanent deflections resulting from slip in the shear connection are less than 5 percent of the nominal elastic yield deflection.

Cambering

Current Specifications and Practice.—The maximum and minimum cambers that can be produced at the mill are specified in the *Manual of Steel Construction* of the American Institute of Steel Construction. For cambers that exceed the maximum allowed by cold-cambering or where reverse or compound curves are required, cambering by heat in fabricating shops is suggested. Although the specifications make no specific mention of heating pattern, they do state:

> The mechanical properties of steels are largely unaffected by heating operations provided that the maximum temperature does not exceed 1100°F. for quenched and tempered alloy steels and 1,200°F. for other steels. The temperature should be carefully checked by temperature-indicating crayons or other suitable means during the heating process.

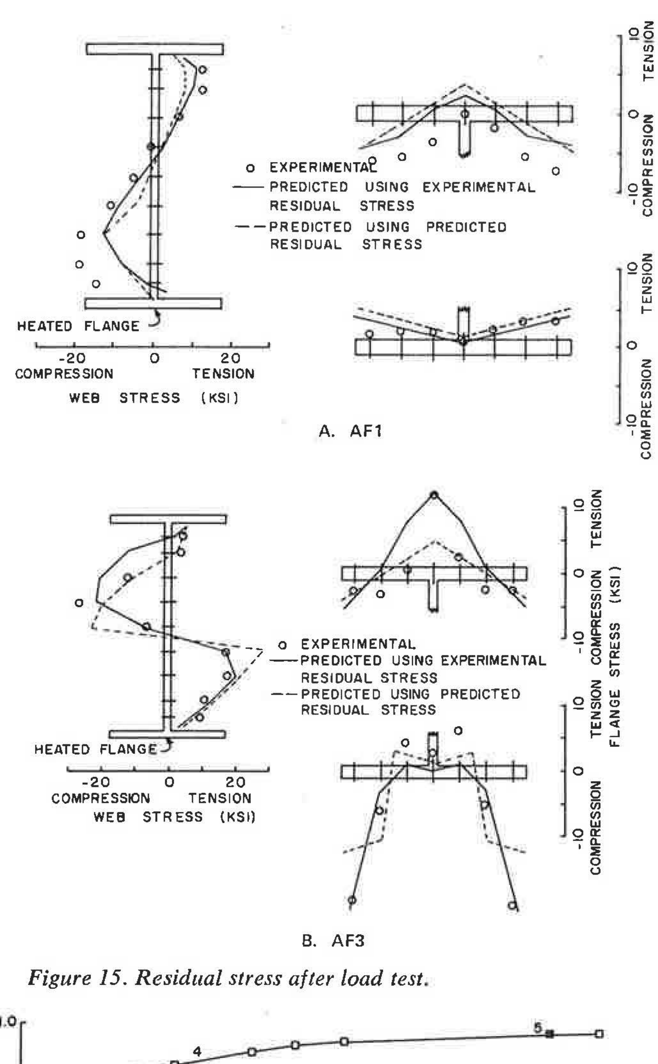


Figure 15. Residual stress after load test.

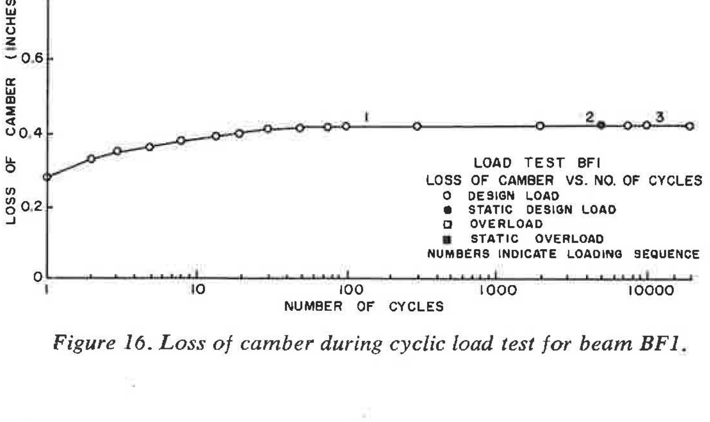


Figure 16. Loss of camber during cyclic load test for beam BF1.

Specifications used in both Wisconsin and New York limit the maximum temperature during heat cambering to 1,200 F. The Wisconsin specifications include:

> . . . The camber shall conform to a uniform, approximately circular curve. . . Camber may be produced either in the rolling mill, or in the fabricating shop by gaging, or it may be produced or corrected by local heating. . . The areas to be heated shall be so selected that distortion other than the required camber will not occur. A procedure shall be followed that precludes warpage of the beam flanges. When such procedure entails heating along the fillets as well as along the center portion of the outer face of the flange, the heat shall be applied to the fillets from each side simultaneously. Cambering by heating vertical sections of the web will not be permitted. Not less than three sections located approximately at the quarter points and at the centerline of the beam shall be heated. The length of each section shall be equal to approximately one and one-half times the depth of the beam. . . .

The primary objective was to duplicate field practice in the laboratory study rather than to satisfy specifications. As a result, only the cold-cambering and continuous-heating procedures satisfied the foregoing specifications. It is interesting to note, however, that those procedures that did not satisfy the specifications seemed to produce the best results.

Both the wedge- and spot-heating procedures greatly exceeded the 1,200 F maximum allowable temperature limit. However, specimens cut from these areas indicated that there was no appreciable grain growth in the steel or any apparent change in physical properties. Thus, there is serious doubt whether some of these restrictions are necessary or even desirable.

Evaluation of Cambering Procedures.—All of the cambering methods examined during this project induced unfavorable residual stress patterns that reduced the elastic limit of the beam and resulted in some (very small, in many specimens) loss of camber under permitted overloads. However, none of the cambering techniques proved to be detrimental to the strength of the beams tested in the laboratory. The residual stresses induced in the flanges by cold-bending were smaller in magnitude than those induced by any of the three flame-cambering procedures investigated. However, because of strain softening (Bauschinger effect), the reduction of the elastic limit and subsequent losses in camber were greater for the cold-cambering method than for two of the flame-cambering procedures. Figure 17 shows these phenomena by means of a plot of moment versus curvature for all of the test beams.

Load versus deflection graphs, shown in Figure 18, were prepared from the moment-curvature relationships. In general, deviations from the initial tangent line indicate permanent deflections or loss of camber. Loss of camber is influenced by the beam span and the lengths and locations of the zones affected by the cambering procedure in addition to the factors affecting curvature. This fact is illustrated by comparing Figures 17A and 18A. The moment-curvature relationships for beams AC2 (cambered) and AF3 are nearly the same, but examination of the load-deflection plot

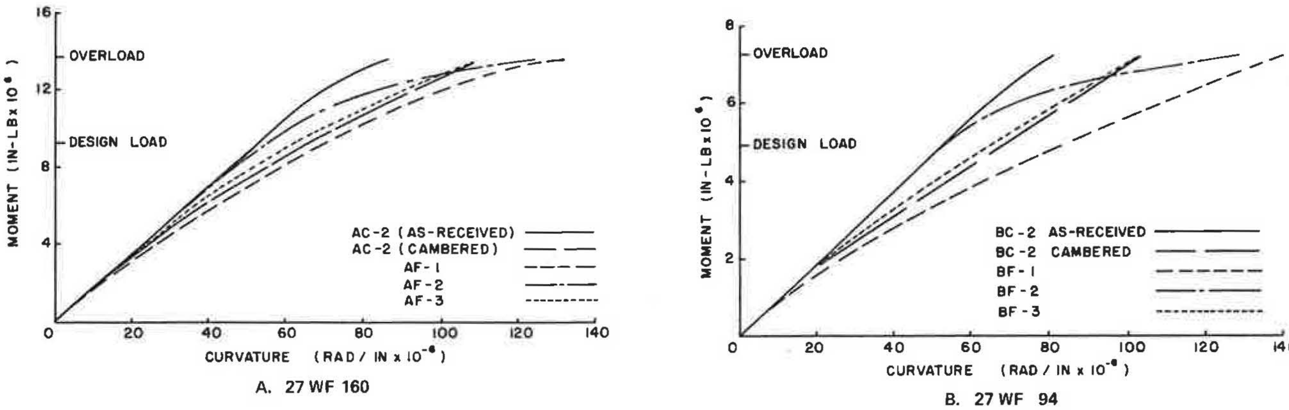


Figure 17. Moment vs curvature for test beams.

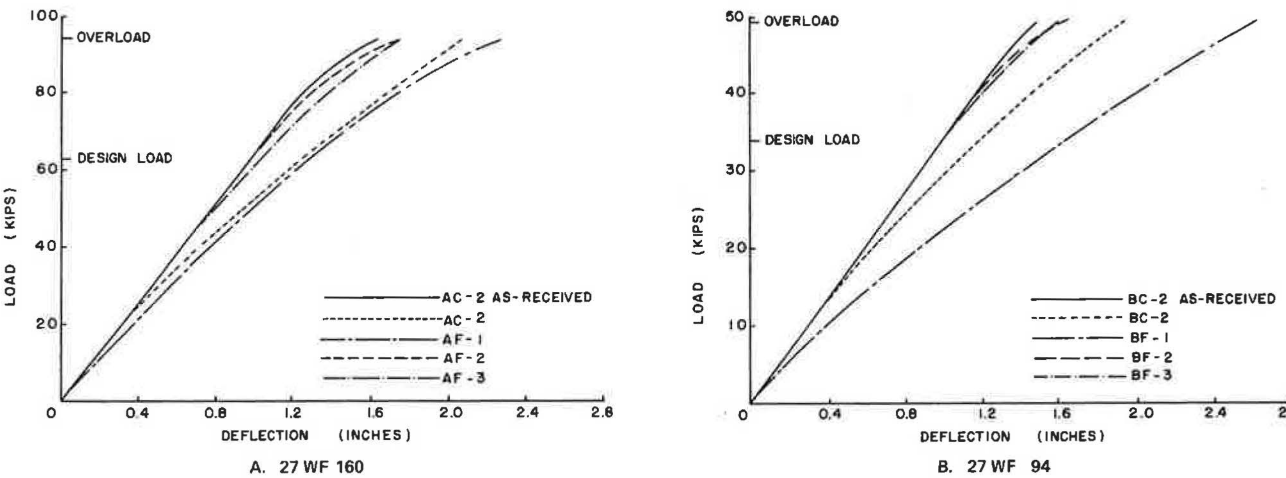


Figure 18. Load vs. deflection for test beams.

shows AC2 to have much greater deflection than AF3 because the spot-heating procedure (AF3) affected only short lengths of the beam while cold-cambering (AC2) affected the entire central section of the span. The point loading used in standard mill cold cambering would probably result in a loss of camber smaller than that of AC2 but larger than that of AF3. Tabular comparisons of camber losses are given in Table 5 as a percentage of the nominal elastic deflection at incipient yielding.

Suggested Cold-Cambering Procedure.—All of the load tests indicated that, regardless of the magnitude of camber or method of cambering, the camber essentially stabilized after the application of one slowly applied cycle of permitted overload. This observation and an understanding of

TABLE 5

PREDICTED VALUES OF PERMANENT CURVATURE OR DEFLECTION EXPRESSED AS PERCENTAGES OF THE NOMINAL ELASTIC YIELD CURVATURE OR DEFLECTION

BEAM	CURVATURE (PERCENTAGE)		DEFLECTION (PERCENTAGE)	
	DESIGN LOAD	OVERLOAD	DESIGN LOAD	OVERLOAD
AC2 as received	0	10	0	10
AC2 cambered	16	37	16	41
AF1	14	53	16	43
AF2	3	48	0	16
AF3	14	32	3	16
BC2 as received	0	4	0	5
BC2 cambered	16	40	14	38
BF1	36	72	32	65
BF2	0	55	0	11
BF3	13	30	2	9

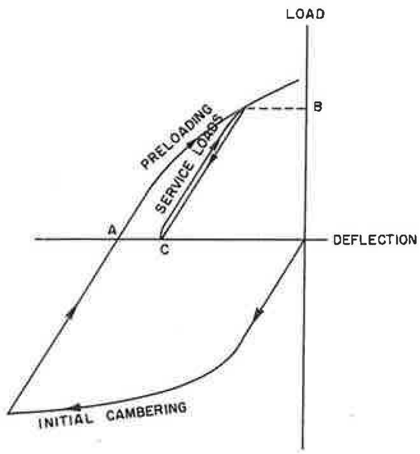


Figure 19. Cambering-overloading procedure.

the mechanism through which loss of camber occurs leads directly to the idea that a bridge could be constructed that would suffer essentially no loss of camber under service conditions if a cycle of overload were applied to beams in the mill or fabricating shop. An overload tends to erase both the undesirable residual stresses and the Bauschinger effect and tends to produce a favorable residual stress pattern, which effectively raises the elastic limit of a beam.

Although the principle of overloading applies to both flame-cambered and cold-cambered beams, the equipment required for overloading would also be suitable for cold bending so that it would probably be more economical to carry out the entire process in a single operation. The cambering process would then proceed as shown in Figure 19, in which point A is the initial camber, point B is the load that produces the allowable overload, and point C is the desired camber. Once the beam had been loaded to point B, the beam would have an elastic behavior at loads below the overload, B.

The application of overload in the mill or fabricating shop would require that the initial camber be greater than the desired camber by an amount equal to or greater than the expected loss of camber. Table 5 indicates that for cold cambering the expected loss of camber is approximately 40 percent of the nominal elastic yield deflection. Since any load equal to or greater than the permitted overload stabilizes the beam, an over-camber of 50 to 60 percent of the nominal elastic deflection at first yielding should be sufficient when cold cambering. To provide proper quality control, both the processes for cambering and overloading should be controlled on the basis of deflection.

Conclusions

1. Because the apparent yield point of a material is sensitive to the rate of loading, yielding may occur in a beam under slowly applied overloads at stresses substantially less than the nominal yield point, which must be satisfied by a standard mill test. This phenomenon is a potential source of permanent deflection in all beams, both cambered and uncambered, and regardless of the cambering method.

2. Residual stresses in as-received beams may be of sufficient magnitude to cause small permanent deflections in beams following permitted overloads.

3. Residual stresses of only 5 or 6 ksi are developed in the flanges during cold cambering. However, a strain softening phenomenon known as the Bauschinger effect combines with the residual stresses to produce losses of camber equal to or greater than those caused by all but one of the flame-cambering methods.

4. Individual beams in a single lot may exhibit wide variations in loss of camber under service conditions if during cold cambering part of the beams are overcambered and subsequently reverse loaded to correct the camber. These variations can result in differential deflections between adjacent beams, which may very well contribute to deck deterioration.

5. Results of this study indicate that very stable beams, which should suffer virtually no loss of camber under service conditions, can be produced if all beams are intentionally overcambered and subsequently reverse loaded to reduce camber to the desired value.

6. Even though there was considerable error in predicting the actual residual stress distributions resulting from flame cambering, both theory and experiment indicate that residual stresses near the yield point are likely to result from all of the flame-cambering processes. These residual stresses in the tension flange of the beam result in some losses of camber under service load conditions.

7. Although the induced residual stresses are rather high, beams cambered by the spot- and wedge-heating methods suffer relatively small camber losses because residual stresses are induced in only small percentages of their lengths.

8. Effective use of the wedge-heating and spot-heating methods seems to require heating of the material above the critical temperature (1,500 F to 1,700 F). However, the A36 steel used in this study underwent apparently no significant metallurgical change and no significant change in mechanical properties.

9. Flame cambering by continuous heating produces high residual stresses throughout the length of the beam that result in large losses of camber.

10. Loss of camber under cyclic loading increases during the first several hundred cycles of load but tends to stabilize at a value approximately equal to the loss following one slowly applied application of load.

11. In composite beams, shrinkage of the deck slab results in permanent deflections that, in most cases, vary between 30 to 60 percent of the elastic deflection caused by dead load of the slab. However, this deflection can be computed and compensated for by increasing camber.

12. Slip in the shear connection of composite beams may reduce the stiffness of the beam 10 to 15 percent, but the contribution to permanent deflection is relatively small.

13. Cold cambering and continuous heating are the most uniform and the easiest processes to model. Consequently, their results are predicted with the greatest accuracy. Because they involve human judgment factors, the spot-heating and wedge-heating processes vary considerably from beam to beam and are extremely difficult to model. As a result, predictions of residual stresses and camber loss are considerably less accurate than for continuous heating and cold cambering.

Project 15-2 FY '66

Design to Control Erosion in Roadside Drainage Channels

By: Dr. Alvin G. Anderson
Research Agency: University of Minnesota

Introduction

The objective of NCHRP Project 15-2 has been to develop criteria and design procedures for the use of aggregate or riprap linings for drainage channels suitable for conditions intermediate between those for which turf cover performs satisfactorily and those for which paved channels or pipe flumes are more economical. The tentative design procedures, developed from analysis of previous research on sediment transport and verified by limited experimental testing in the hydraulics laboratory, were published in *NCHRP Report 108,* "Tentative Design Procedures for Riprap-Lined Channels." During the field evaluation phase of the study, riprap linings for five channels were designed in accordance with the procedures described in Report 108. Four of the channels have been constructed and are performing satisfactorily. Two have been subjected to discharges approaching the design discharges without signs of erosion.

Findings

The drainage channels designed and constructed in accordance with the procedures described in Report 108 and subjected to field evaluation are listed in Table 1. Data used in the design of the riprap lining for each channel, and photographs of performance, are included in the field evaluation report, which has been distributed to all state highway agencies.

The Hop Brook site in Manchester, Conn., is a stream relocation with a design discharge much greater than that initially intended to be included within the scope of the project. The study procedures were extrapolated to determine the desired riprap size and the cost estimate for the 4,400-ft-long relocation compared with the cost of a paved lining. The riprap lining was constructed at an estimated saving of $94,000. The only evidence of stress after several years of use has been localized at the side inlets where excess energy from the inlet flow was not appropriately dissipated. This situation was easily corrected during maintenance operations.

The channel at Moose Lake, Minn., was also a stream relocation between a railroad embankment and a highway. During the first year after construction the channel was subjected to a flow near the design discharge as a result of unusually heavy rainstorms in the area. Inspection indicated that the channel effectively withstood the attack of the flood flow.

The field evaluation sections in Wisconsin and Montana were typical roadway channels with relatively small design discharges. The roadside ditch along a two-lane highway in a sandy soil area of Chippewa County, Wis., was unstable and in need of some type of erosion control. A locally available gravel was selected as the riprap lining

TABLE 1

DRAINAGE CHANNELS DESIGNED ACCORDING TO PROPOSED TENTATIVE DESIGN PROCEDURES

Location	Present State	Design Q (cfs)	Design Slope	Riprap d_{50} (ft) Design	Riprap d_{50} (ft) Used	Bottom Width (ft)	Side Slopes	Design Depth (ft)	Max. Q to date (cfs)[a]	Present Condition
Manchester, Conn.	Const. 1969	3900	0.007	1.06	1.5	20	2:1	9.15	1500	Very good, vegetation on sides and top. Mean size of riprap appears to vary somewhat along channel.
Moose Lake, Minn.	Const. 1971	275	0.003	0.21	0.25	12	3:1	4.0	250	Channel very good. All riprap in place. Erosion at outlet of culvert at upstream end.
Klamath Falls, Ore.	Design	1100	0.0054	0.43		15	2.5:1	5.3	-	Chandler Wayside Park
Chippewa County, Wis.	Const. 1969	6	0.017	0.08	0.08	10	4:1	0.5	-	Roadside drainage. Good condition. Some damage from truck wheels.
Montana I-90-8(66)	Const. 1971	18	0.05	0.6	0.33	0	6:1	-	-	Median strip. Appears to be in good condition. Riprap gravel uniformly graded 2-in. minimum to 8-in. maximum.

[a]Approximate.