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FATIGUE OF CURVED STEEL BRIDGE ELEMENTS

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FATIGUE OF CURVED STEEL BRIDGE ELEMENTS

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INTRODUCTION

Within the past decade there has been a rising utilization of curved girders in highway bridges. In conforming to nonaligned roadway approaches, curved supporting elements tend to be more aesthetic than straight girder segments and reduce construction costs. However, the design of curved girders is considerably more difficult due to a relative lack of experience, more complicated structural action (particularly with regard to torsion), few design code guidelines, and until recently, comparatively little supporting research.

In the late 1960's the FHWA (Federal Highway Administration, U.S. Department of Transportation) commenced the CURT (Consortium of University Research Teams) Project in an effort to develop detailed curved girder design guidelines for inclusion in the AASHTO bridge code. By the close of 1973 the project had produced specification recommendations for both open and closed section curved girders. Also, numerous computer programs with varied capabilities were generated. Several areas of additional research needs were identified -- one of these was steel curved girder fatigue.

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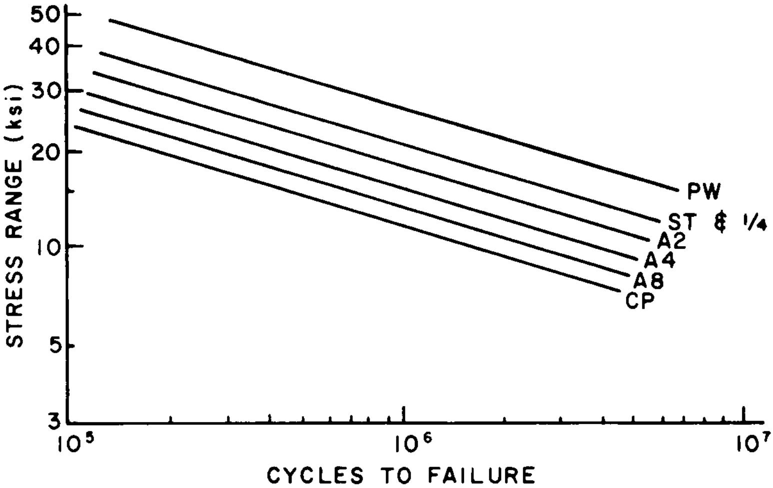
Fortunately, the 1960's also saw considerable progress in understanding and predicting steel straight girder fatigue. Among several investigators, John W. Fisher of Lehigh University showed that the dominant variables are bending stress range and the type (length) of detail (attachment).[1,2] Figure 1 demonstrates that the relationship is logarithmic for different attachment sizes. Other variables such as maximum stress, stress ratio, and type of steel had little affect on the results. Fisher also observed that a large portion of the fatigue life (65-95%) was expended in transforming the near surface weld flaw to a crack through the girder flange or web plate. The result of Fisher's work is the AASHTO code revision represented by Table 1.[3]

The intersecting courses of curved girder and fatigue research have quite naturally led to the project discussed in this paper. In October 1973 Lehigh University was awarded an FHWA contract to study fatigue in steel curved girders -- both open and closed section. The overall intent is to compare fatigue behavior in curved elements with straight girder performance, and suggest AASHTO code revisions as required.

TECHNICAL ASPECTS

1. CRACK GROWTH RATE

One might well ask why there should be any difference in fatigue provisions for straight and curved girders. The details of curved elements are merely subjected to applied loads and don't, in themselves, actually "see" the curvature. While this point is well taken it is



KEY:

PW - Plain Welded
ST & ¼ - Stiffeners and ¼" Attachments
A2 - 2" Attachments
A4 - 4" Attachments
A8 - 8" Attachments
CP - Cover Plated

Fig. 1 Summary of S-N Plots for Flange Attachments and Transverse Stiffeners (2)

TABLE 1 [a]

Category	Allowable Range of Stress, F_{sr} (ksi), for			
	100,000 Cycles	500,000 Cycles	2,000,000 Cycles	over 2,000,000 Cycles
A	60	36	24	24
B	45	27.5	18	16
C	32	19	13	10
D	27	16	10	7
E	21	12.5	8	5
F	15	12	9	8

[a] AASHO Table 1.7.3B.

the kind of loads at the details which is of concern; in curved girders the loading is much more complex. Besides bending shear and normal stresses at a typical section, curved girders usually resist warping normal and shear stresses as well as pure torsion shear stress. Also, for details which function as connection points for transverse cross bracing, diaphragms, or bottom lateral bracing, significant biaxial and occasionally triaxial stresses are often induced.

It is reasonable to expect therefore that the presence of additional stresses at details could affect the growth rate -- particularly in cases where the normal bending stress is not clearly dominant. The simple use of bending stress range for fatigue life prediction, as in straight girders, might no longer be valid. Even the total normal stress range (bending plus warping) may not be an accurate barometer. The use of principal stresses may be inescapable.

The Paris formula for crack growth rate is given below.

$$\frac{da}{dn} = C\,(\Delta K)^n$$

where $\frac{da}{dn}$ = crack growth in inches per cycle

ΔK = stress-intensity factor range in ksi $\sqrt{in.}$

The approximate values of the constants C and n from Fisher's work are 2×10^{-10} and 3, respectively. The stress-intensity, K, is that associated with stress perpendicular to the crack propogation direction. (In fracture mechanics jargon this is called opening mode or mode I.[4])

For a surface crack initially not aligned with principal stress directions it is evident that shear stresses must exist at the crack tip in addition to perpendicular and parallel axial stresses. If the alignment does not change significantly before the crack is driven through the steel flange or web, much of the fatigue life is spent under the influence of stress interaction (modes I, II, and III)[4]. Fisher did not actually consider alignment; he merely found the maximum principal stress at the weld and assumed the crack or flaw was perpendicular to it. (The principal stress in this instance was based on a nearby normal bending stress and the stress concentration effect of the detail geometry. As mentioned previously, nearby bending shear stress was not considered.) This assumption needs reexamination. It may be necessary to have more than one ΔK term in the Paris equation and/or to modify the C and n values.

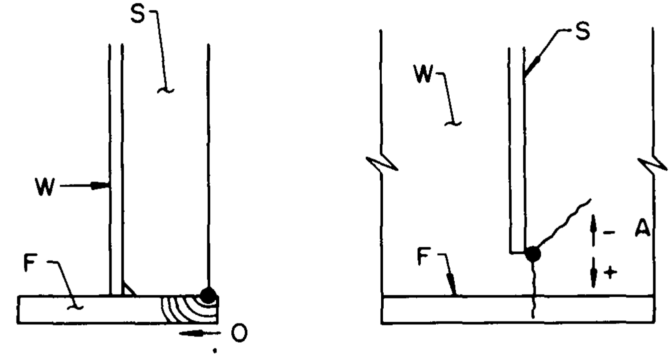
2. WARPING STRESS RANGE GRADIENT

If the crack growth after the crack is through the plate reppresents a significant portion of fatigue life of curved girders, normal stress gradients will have to be considered. The flanges of straight girders have no gradient unless the member is specifically loaded in torsion. With curved girders there is always torsion and, particularly in open section elements, the warping normal stress gradient can be quite high. Generally, the smaller the horizontal radius the higher the gradient. However, it is important to realize that the gradient also varies significantly between transverse bracing locations. The in-plane bending of the flange can be likened to that of a continuous girder where the bracing represents the supports.

Three common situations of crack growth in straight girders are given in Figures 2(a) through 2(c).[2] Several possibilities associated with curved girders are shown in Figures 3(a) through 3(c). (These figures are not intended to be all inclusive.) A distinguishing point in the curved situation is that crack arrest in the flange is possible in certain instances. Also, as implied by the discussion of crack growth rate, the crack may not grow perpendicular to the longitudinal direction (Figure 4). In some cases this could aid crack arrest. However, stress redistribution is likely as the crack enlargens and may complicate the problem.

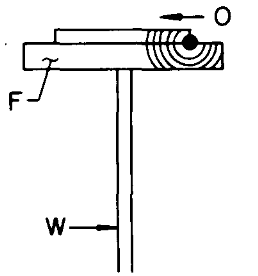
It is worthwhile recalling that the stress-intensity factor, K, is dependent on both flaw size and stress. The highest value of ΔK determines where fatigue crack propagation initiates. Therefore, the critical location is not necessarily that of the largest stress or largest flaw size. In the flanges of straight girders the stress is typically constant and the crack simply emanates from the largest weld flaw. For curved girders with flange normal stress gradients the critical flaws may be other than the largest at a given section.

Straight girder fatigue research has found no substantive importance in the gradient question due to the small percentage of life associated therewith. In part, this conclusion resulted from the definition of failure by a deflection criterion.[1,2] The deflection limit was set such that when attained, the crack had propagated through enough of the flange for net section yielding to occur. Because of stress gradients present in curved girder flanges and potential crack arrest, it may be desirable and even necessary to redefine failure. Also, the question of stress redistribution should be addressed.



(a) Stiffener Welded to Flange

(b) Stiffener Cut Short

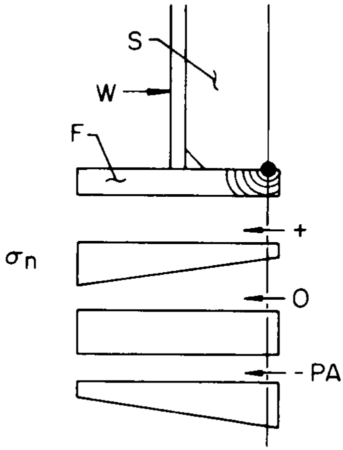


(c) Cover Plate Termination

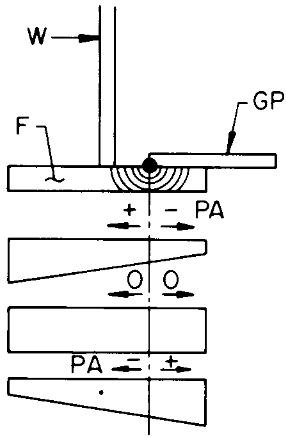
KEY:

←	Crack Growth Direction
σ_n	Normal Stress
0	No Normal Stress Gradient
+	Positive Normal Stress Gradient
-	Negative Normal Stress Gradient
A	Arrest
PA	Possible Arrest
F	Flange
S	Stiffener
W	Web
●	Critical Weld Flaw (actual or predicted)
GP	Gusset Plate

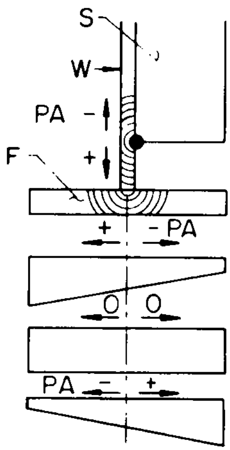
Fig. 2 Straight Girder Stress Gradients



(a) Stiffener Welded to Flange



(b) Gusset Plate Attachment



(c) Stiffener Cut Short

Fig. 3 Curved Girder Stress Gradients (see KEY Fig. 2)

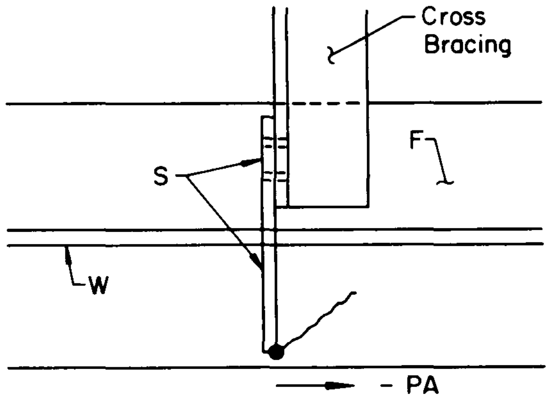


Fig. 4 Potential Crack Growth In Flange
(see KEY for Fig. 2)

3. "OIL CANNING" EFFECT"

Another goal of the present curved girder investigation is to evaluate the newly suggested web slenderness ratios with regard to fatigue performance at the web boundaries.[5] Straight girder webs have already undergone a similar study.[6,7] Generally, it is not expected that fatigue at web boundaries is more critical than fatigue at attachment locations. However, the web slenderness ratio and panel aspect ratio are known to affect the relative importance of web versus attachment fatigue.

TEST PROGRAM

1. CONTENT

Both open (I-girder) and closed (box girder) steel sections are to be tested. Since it is primarily the conditions at welded details which are of interest, the test assemblies are designed such that a realistic bridge stress field is simulated at real life details. This does not mean that the overall assemblies are identical with a true bridge structure although the section and detail sizing are to be typical, and everything else of large dimension.

To date considerable progress has been made on the open section portion of the project. Five two-girder assemblies, as shown in Figure 5, each with common overall geometry, comprise the test program. Various detail attachments are to be spotted at bracing locations as well as between them. Two concentrated loads of 100 kip range are to be imposed on the center line at the quarter points of the span. None of the assemblies is to have a slab.

Stress analyses of the open section assemblies were carried out by means of two CURT-generated computer programs. Preliminary design was done using the Syracuse program; final design work was performed with CURVBRG by G.H. Powell of the University of California at Berkeley. CURVBRG was found to be particularly useful in that it possessed such features as automatic nodal point and section property generation, output of stresses at key points in a given cross section, output of stresses at node and non-node locations, possible inclusion

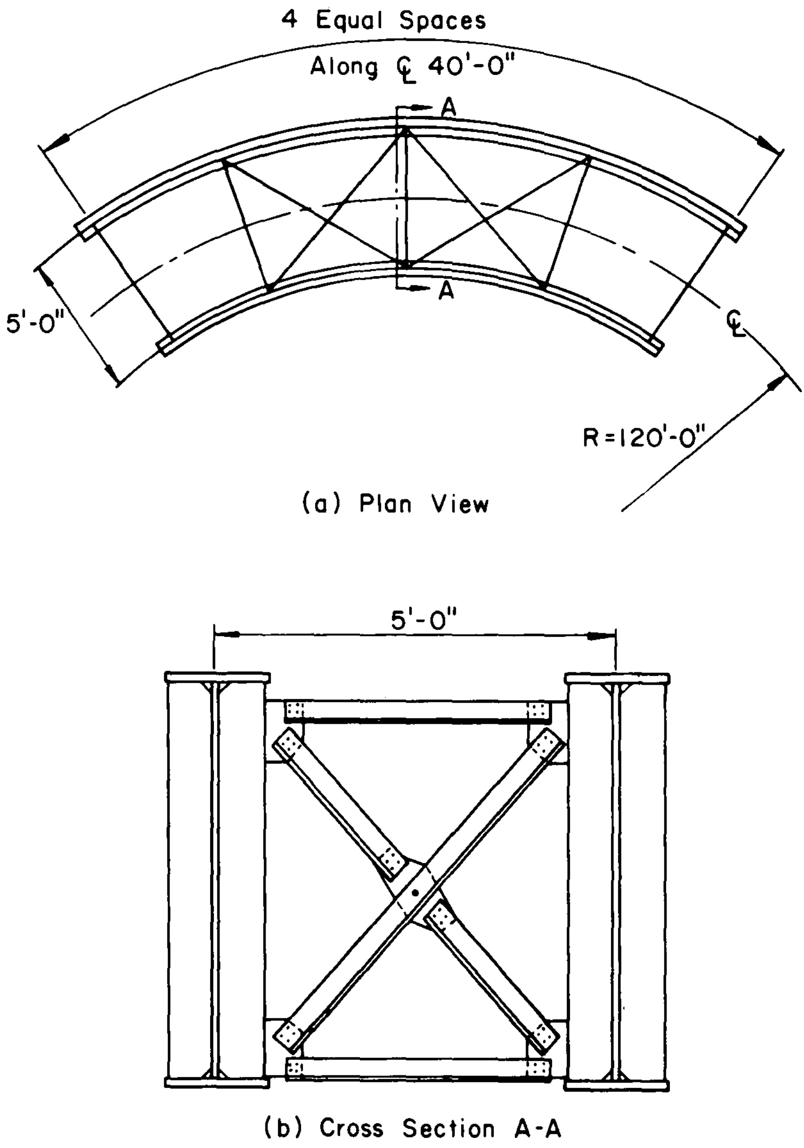


Fig. 5 Typical Test Assembly

of composite and non-composite diaphragms, possible inclusion of bottom lateral bracing, possible inclusion of a bridge deck, and the capability of handling simple or continuous spans.

The box girder investigations got underway in July 1974. Two computer programs from outside the CURT Project have aided in the analysis. They are SAP IV (a finite element program by E Wilson of Berkeley) and CURDI (a finite strip program by A. Scordelis of Berkeley). The final geometry and details of the box assemblies have not yet been resolved. However, there are expected to be five test assemblies of about the same overall dimensions as in the open section study.

2. DETAILS

Five specific types of details are being investigated in the open section test program (Figures 6(a) - 6(e)). Three of the details are flange attachments and two are web attachments. Based on the length of the details, all fall into category C or E of Table 1 (for straight girders). Approximately 12 of each attachment are to be included in the five tests for repetition (statistical) purposes. Some of each type will be situated at cross bracing locations.

3. WEB PANELS

Generally oil canning effects are expected to be most prominent in the outer girder of each assembly. Thus, stiffener spacing and the web slenderness ratio have been varied in this member. Slenderness

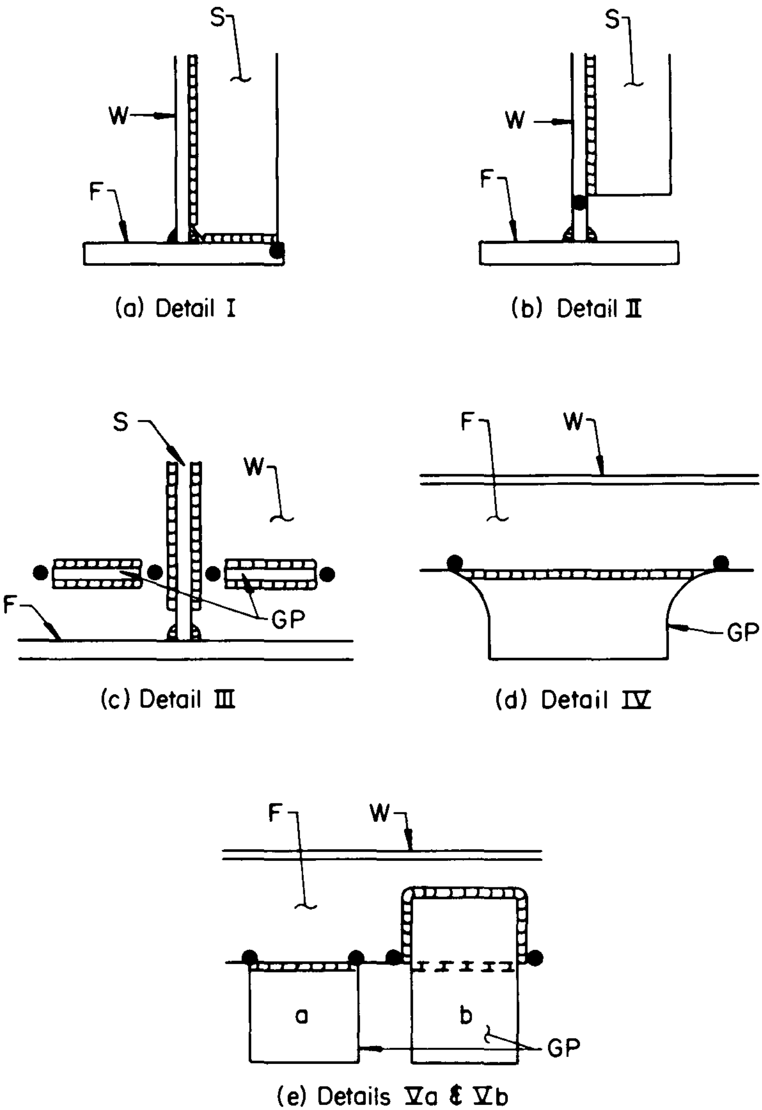


Fig. 6 Summary of Details
(see KEY Fig. 2)

variance has been partly responsible for a web bending stress which differs between assemblies. The philosophy is to exceed the stiffener spacing limits prescribed by Reference 4 in some instances and not in others. Thereby the adequacy of the recommendation, as far as fatigue is concerned, can be judged.

SUMMARY

Lehigh University has been awarded a research contract by FHWA to study fatigue of curved steel bridge elements. The project began in October 1973 and is to continue into September 1976. Both open and closed sections are included in the test program. To date, five two-girder open section test assemblies have been designed and are in the fabrication stage.

The project is specifically aimed at evaluating the fatigue performance of welded details (including web panel boundaries). Crack growth rate and the importance of warping stress range gradient are to be established. Recommendations for revisions to the fatigue portion of the AASHTO bridge code are to be made, if required.

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