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A SUMMARY REPORT ON THE BEHAVIOR OF THIN-WEB PLATE GIRDERS UNDER REPEATED LOADING

by

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SYNOPSIS

Thin-web plate girders behave in a different manner than beams when subjected to repeated loading. Repeated lateral web movements cause fatigue cracks along web boundaries. The pattern of web deflections under load, the occurrence of cracks and their locations, and the estimate of stresses in girders are all described on the basis of experimental and analytical results. The possibility of using slender-web girders for highway bridges is discussed.

INTRODUCTION

Plate girders are common bridge members for carrying bending moments and shearing forces beyond the capacities of beams. Plate girders usually are much deeper than beams and their deep web plates are susceptible to lateral buckling. The elimination of the possibility of web buckling long has provided a limit in bridge girder design. Specifically, the web depth to thickness ratio (the slenderness ratio) and the spacing of transverse stiffeners are kept low so that web panels will not buckle. The consequence is that the functioning of a plate girder is identical to that of a beam.

Results of studies have shown that a sudden web buckling phenomenon does not exist in steel plate girders (1) and that the static load carrying capacity of a plate girder is not its web buckling load (2,3,4). Based on analytical methods of static strength evaluation, girders for buildings are no longer designed by the web buckling theory. Thin webs are permitted and stiffeners are spaced relatively far apart in such girders (5).

For plate girders in bridges, the utilization of the above-mentioned post-buckling strength can be made only after the fatigue behavior of girders under repeated loading has been investigated. Since a girder is essentially a beam--except for the web--and since numerous fatigue studies have been made on beams (6), the emphasis here is on the behavior of girder webs, or web panels.

MOVEMENT OF PLATE GIRDER WEBS

Under gradually applied loads on a girder, the web of a panel deflects laterally in a gradual manner. For a particular point on the web, the load-lateral deflection relationship generally takes one of the two forms of Fig. 1 (7). At points of compression and high shear, deflections are relatively large at high loads and their relationship is not linear (Fig. 1a). Points in the tension region of a girder panel usually decrease their deflection when more load is applied (Fig. 1b). In both cases, there are initial lateral deflections or out-of-straightness of the web; and there is no sudden "buckling" as would have been indicated by a discontinuity of the $P - \Delta$ curves. The magnitudes of these deflections depend on the geometry of the panel and the location of the point in question. Points far away from the panel boundaries usually have much larger deflection magnitudes than those of points near the flanges and stiffeners. Thin web plates usually deflect much more than thick plates.

When repeated loads are applied on a girder, each load cycle constitutes a gradual increase and decrease of load within the period of the loading. The lateral deflection of a point increases and decreases with the load as described by the $P - \Delta$ diagrams above. The result is that, under repeated loads, web points move laterally back and forth (Fig. 2). This movement is synchronized with the repeated loading and is characteristic of thin-web plate girders (8).

Cross-sectional shapes of thin-web girders under loads have been measured (7) and the results, when sketched out, give a pictorial indication of the web movement (Fig. 3). If the applied load fluctuates repeatedly between two magnitudes, the cross sections of the web move repeatedly laterally between two deflected positions. It is quite clear then that thin-web plate girders under fatigue loading are subjected to repeated bending (secondary bending) of the web plate.

Because the lateral movement of a web panel involves all points within the panel, the deflected shape of the whole web, rather than that of cross sections or the P - Δ diagrams of individual web points, is more descriptive in revealing the behavior of the web. Lateral deflection contours of web panels therefore are constructed. Depending upon the loading condition on a panel, there are three patterns of deflection contours for thin-web panels (7). Under pure bending moment, the compression zone of a web panel deflects much more than the tension region, as is indicated by the close distance between contour lines in the upper part of the panel in Fig. 4. At high shear, a pattern of inclined contour lines is usually present (Fig. 5). The inclination follows generally the direction of the panel's tension diagonal. When both bending moment and shearing forces are appreciable, the pattern of the lateral deflection contours is the combination of the previous two. The typical inclined contour lines for shear are dominant and the magnitudes of deflections are higher in the compression zone (Fig. 6). In any of the three cases, a thin web of a girder panel moves between two deflected positions of similar pattern when the fatigue load range is small, or between a relatively flat position and that of Figs. 4, 5 and 6 when the load range is large.

The significant phenomenon is that plate girder webs repeatedly move laterally in synchronization with the loads on the girder (8). The movement, although small for relatively thick webs, is nevertheless measurable. For thin webs, this movement can be seen by eye if the web slenderness ratio is high, if stiffeners are spaced far apart, or when high loads (as compared to the static strength of the girder) are applied.

FATIGUE FAILURE OF THIN WEBS

The consequence of lateral web movement is the possibility of fatigue crack formation along web boundaries. Results of experimental investigations show that, indeed, such cracks occur in thin webs at high loads and large load ranges (8,9,10). These cracks are usually observed at the web toes of the boundary fillet welds in welded plate girders, very often initiate on one surface of the web and then propagate through the thickness to the opposite surface (8).

The uniqueness of these fatigue cracks in the web is that they were not detected in beams where webs do not move laterally. Also, these cracks differ from other beam and girder fatigue cracks--such as those at the termination of transverse stiffeners or partial length coverplates--in that the web cracks have much less apparent effect on the fatigue performance of the member. Often with web cracks of considerable length, a plate girder can continue to sustain fatigue test loads without increasing deflections.

If the initiation of fatigue cracks in the web is considered the failure of the web panel, then failure modes of thin-web panels of plate girders may be classified according to their loading conditions (8). In a "shear mode" of failure, where high shearing forces are applied to a panel and an inclined pattern of web deflection contours is present, web cracks may appear along the flanges or the transverse stiffeners at short distances away from the corners of the panel where the tension diagonal is present (Fig. 7). For panels in pure bending the more frequent cracks are those near the tension ends of transverse stiffeners which are common to beams as well as to girders. In addition, a possible location of web cracks is along the transverse stiffeners just below the neutral axis (Fig. 8). In a failure mode of combined bending and shear, the effects of large lateral web deflections in the compression region cause web cracks to occur more likely along the upper boundaries of the web panel (Fig. 9).

Definitions of fatigue failure notwithstanding, it seems certain that the initiation of web cracks is as much related to the lateral movement of the web as to other factors such as local stress concentrations and primary stresses. When subjected to high magnitudes of lateral web deflections, cracks along web boundaries generally (but not always) develop earlier than when the deflections are small. The more important fact is that only when the lateral web deflections are of high magnitudes do the webs crack along the boundaries.

STUDY OF WEB STRESSES

The correlation between lateral web deflections and web boundary cracks is through the evaluation of stresses at the boundaries. High magnitudes of deflections may create high stresses which in turn cause fatigue cracks. Hence, the obvious procedure to investigate fatigue cracks in thin-web plate girders is to evaluate stresses along the web boundaries from web deflections and then consider the stress-cycle relationship (S-N curves). Unfortunately, up to the present, there are no applicable accurate mathematical solutions to relate deflections and stresses because of the complexity of initial deflections and the uncertainty of boundary restraints to the web. Neither is there sufficient information to construct S-N curves for web boundaries. Experimental or semi-empirical methods have to be employed.

From measurements made during plate girder tests, it has been found that secondary web bending stresses due to lateral deflections of the web can be as high as the yield point of the girder material (8). At certain locations of cracks where no direct measurements were made, simple assumptions give approximate values of these stresses from measured web deflections. For the few cracks where approximation is possible, the resulting stress-cycle relationship shows a definite trend (Fig. 10) similar to that of common S-N curves. Further study in this direction is in progress.

CONCLUSIONS AND DISCUSSION

From the very brief description above on the behavior of thin webs of plate girders, it can be concluded that:

1. Plate girders differ from beams in that some finite amount of lateral web deflection takes place in girders subjected to load.
2. If repeated loads are applied to a girder, its web moves repeatedly between two lateral positions and in synchronization with the load.
3. The consequence of severe lateral web movement is the possibility of fatigue cracks along the boundaries of thin webs.
4. Modes of fatigue cracks in girder panels depend on the patterns of lateral web deflections which, in turn, are governed by the loading conditions on the web panels.
5. Stresses due to lateral deflections of thin webs can be as high as the yield point of the girder material. An empirical stress-cycle relationship for web boundary cracks has the familiar shape of common S-N curves.

Based on the research work conducted thus far, it is anticipated that the web buckling limitation will be relaxed in bridge girder design. Although the use of more slender webs has the potential of causing fatigue cracks, it is no more severe than that created by current bridge details such as transverse stiffeners and partial-length coverplates. Whereas these details are permitted with precaution, it seems logical also to permit the use of more slender webs, with proper limitations. These limitations probably will be expressed through the web slenderness ratio or stiffener spacing which will prevent excessive lateral web deflections.

ACKNOWLEDGEMENTS

The results summarized in this report are from investigations on welded plate girders conducted at Fritz Engineering Laboratory of the Civil Engineering Department, Lehigh University, Bethlehem, Pennsylvania of which Dr. Lynn S. Beedle is the Director. The sponsors of the investigations have been the Pennsylvania Department of Highways, the U. S. Bureau of Public Roads, the American Iron and Steel Institute (Subcommittee of Steel Plate Producers), the American Institute of Steel Construction, and the Welding Research Council. The encouragement and assistance of the members of the Welding Research Council Subcommittee on Welded Plate Girders are gratefully acknowledged. Special thanks are due the colleagues who have worked on the project.

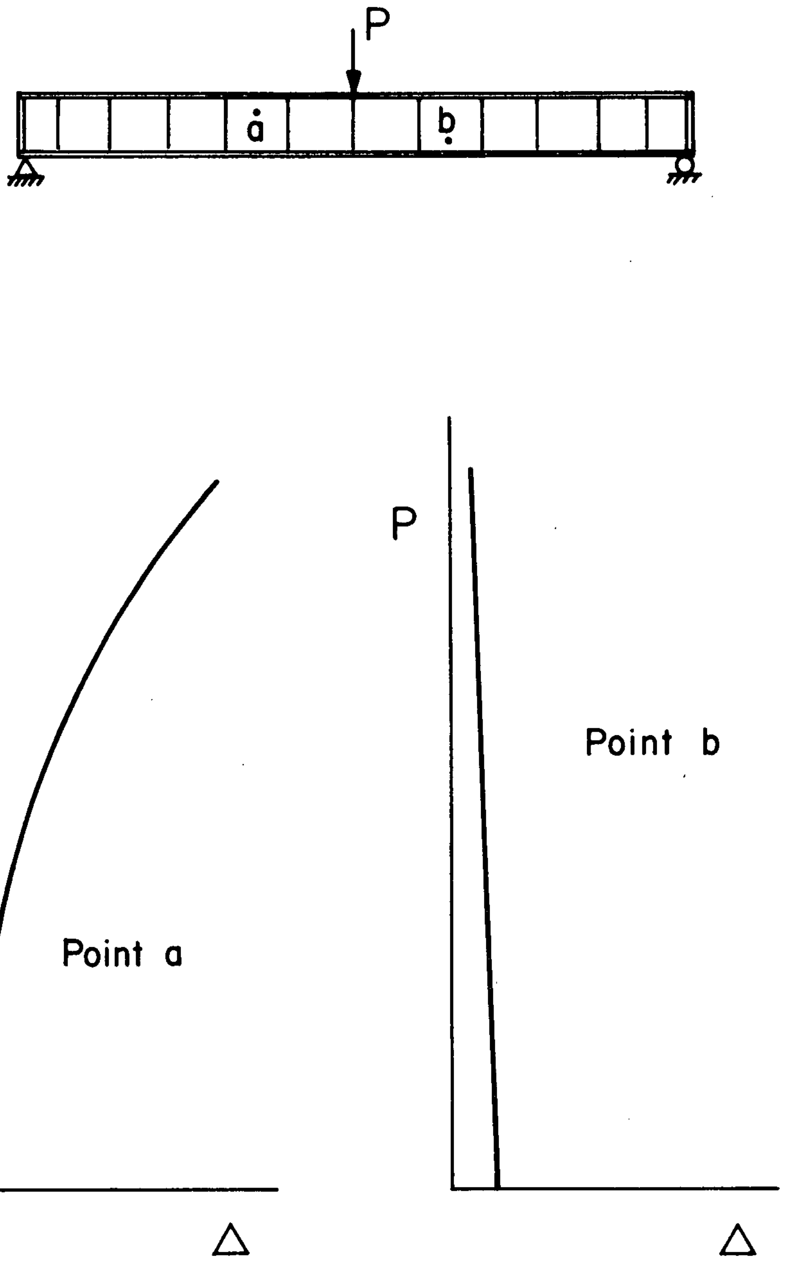

Fig. 1 Load Versus Lateral Deflection of Web

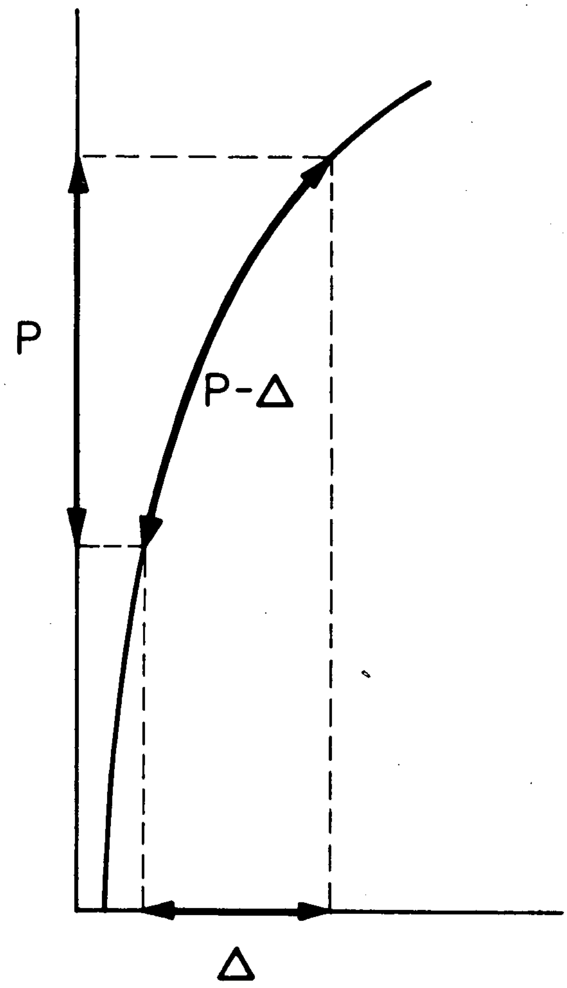

Fig. 2 Web Fluctuation Under Repeated Load

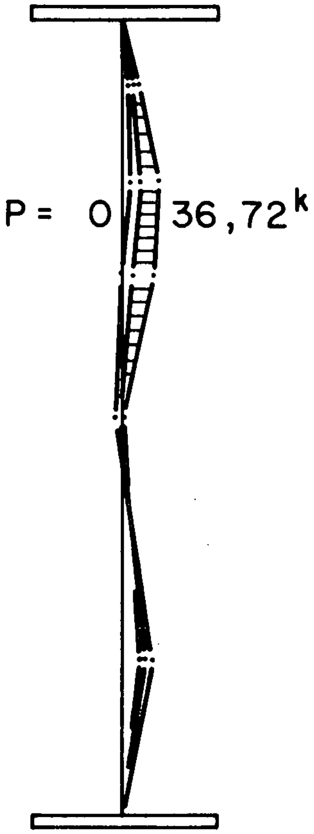

Fig. 3 Laterally Deflected Web Cross Section
(deflections exaggerated)

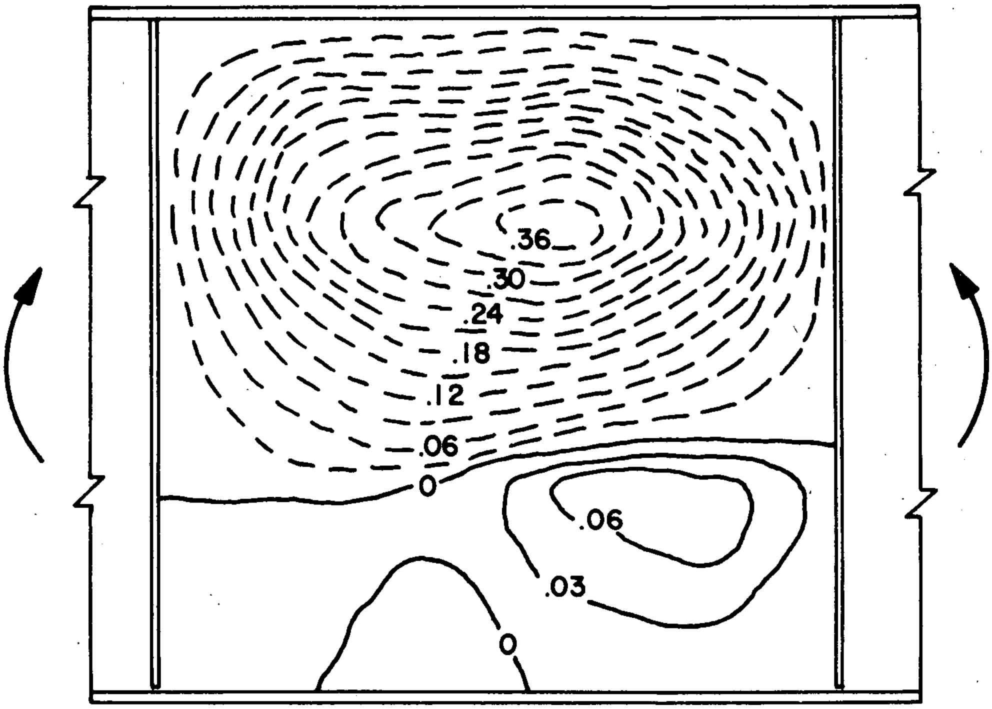

Fig. 4 Lateral Web Deflection Contour, Panel Under Bending

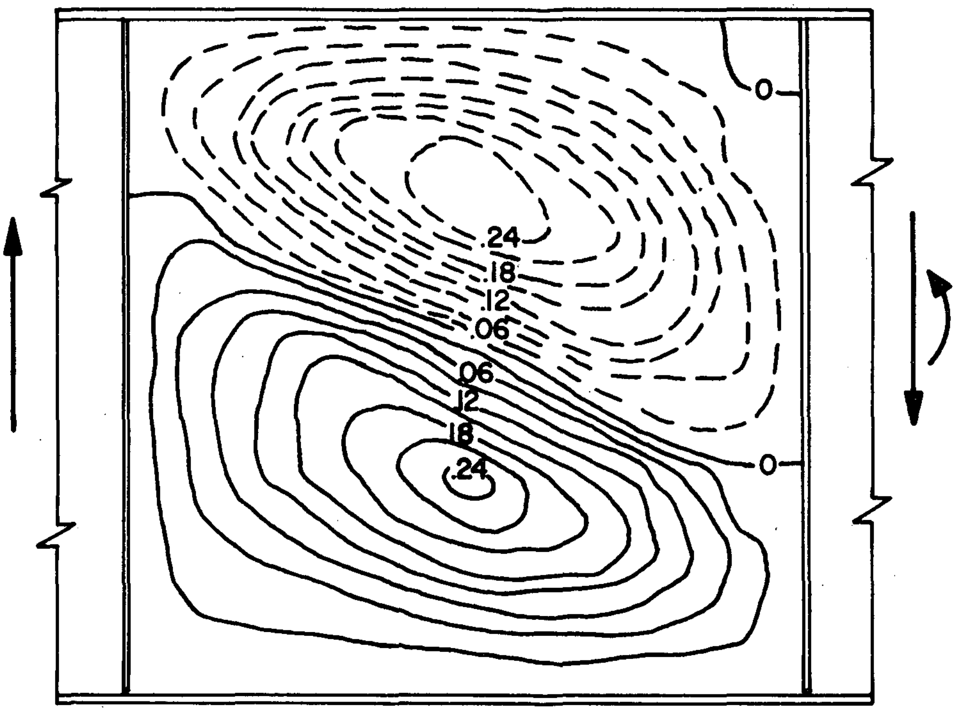

Fig. 5 Lateral Web Deflection Contour, Panel In Shear

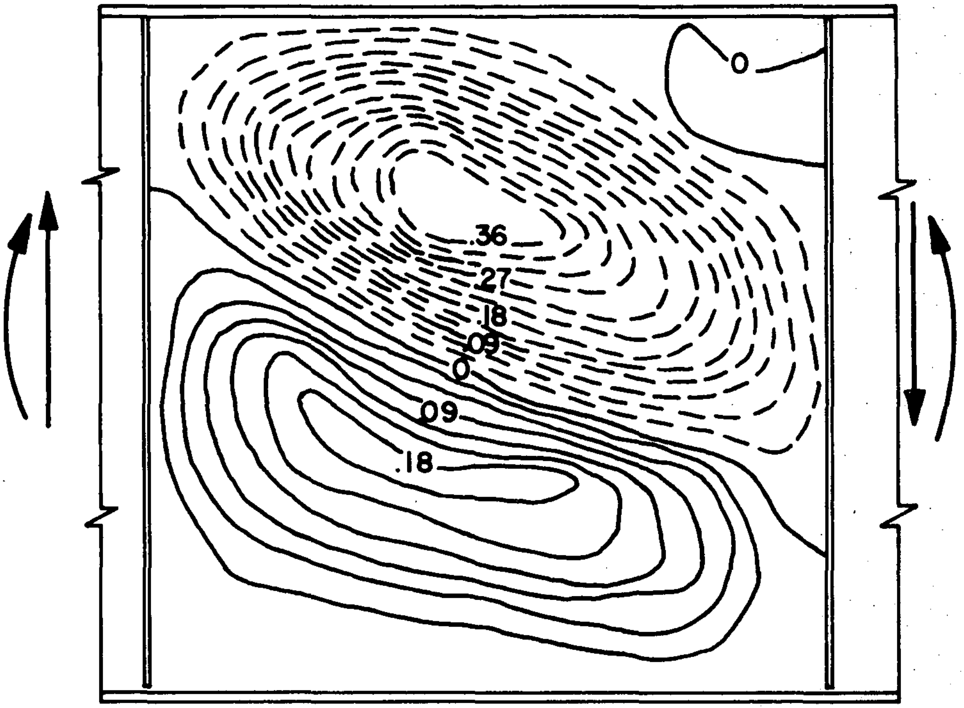

Fig. 6 Lateral Web Deflection Contour, Panel Under Combined Bending and Shear

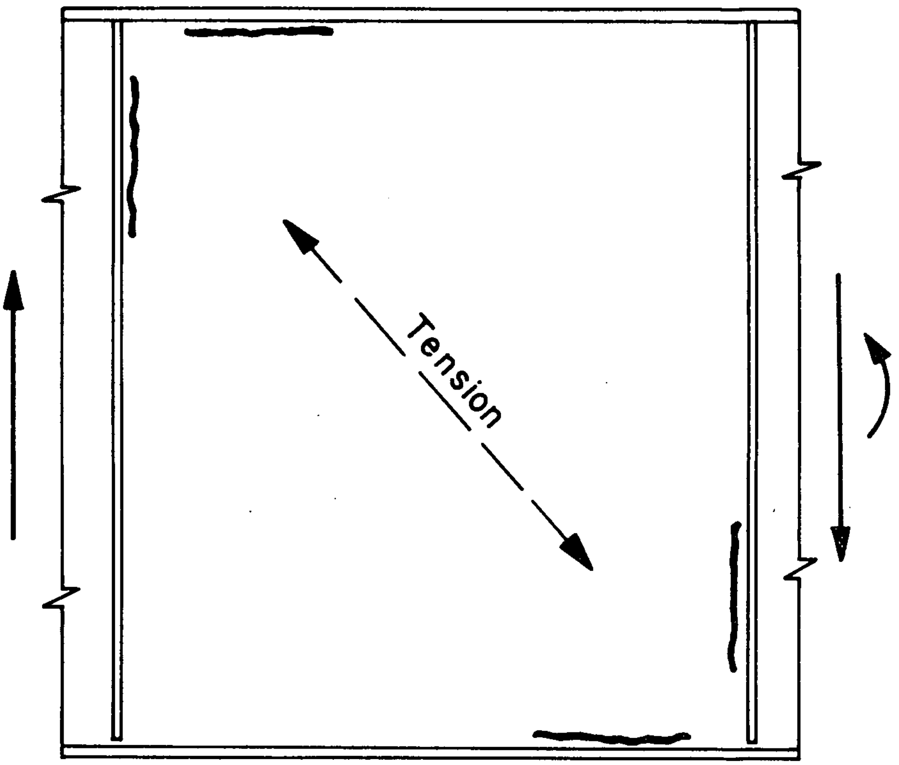

Fig. 7 Locations of Web Cracks, Panel in Shear

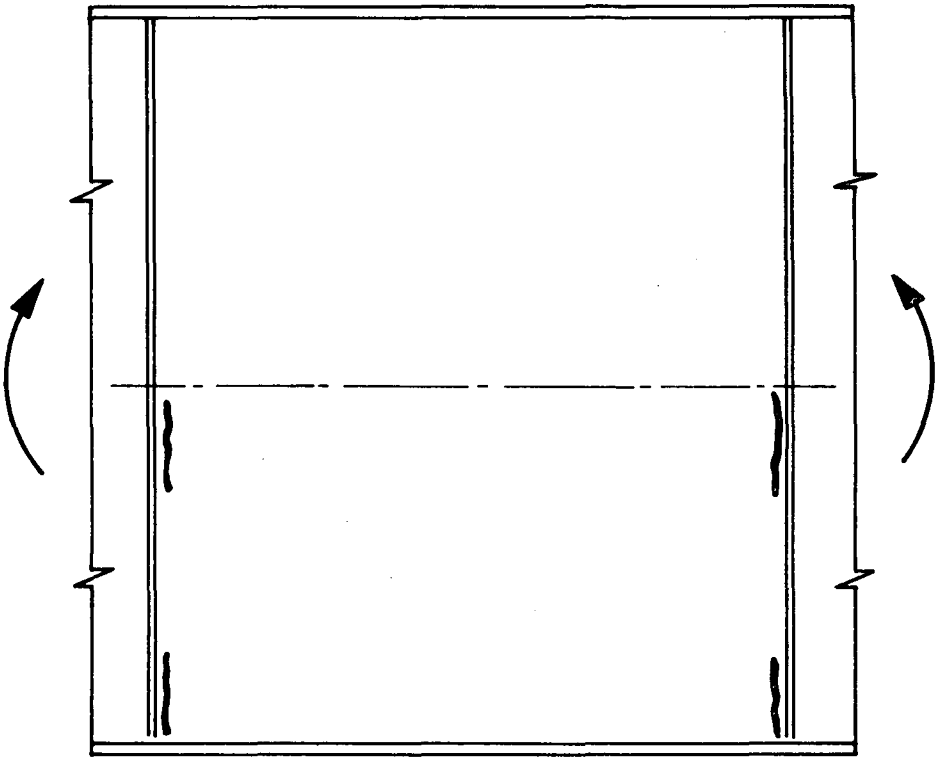

Fig. 8 Locations of Web Cracks, Panel in Bending

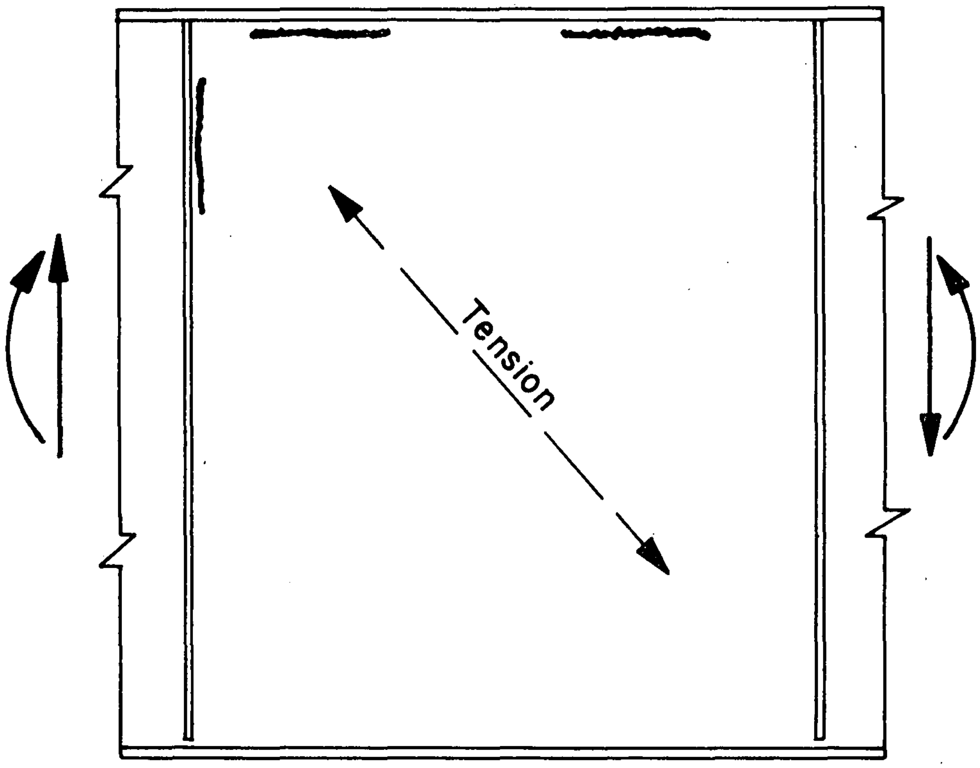

Fig. 9 Locations of Web Cracks, Panel Under Combined Bending and Shear

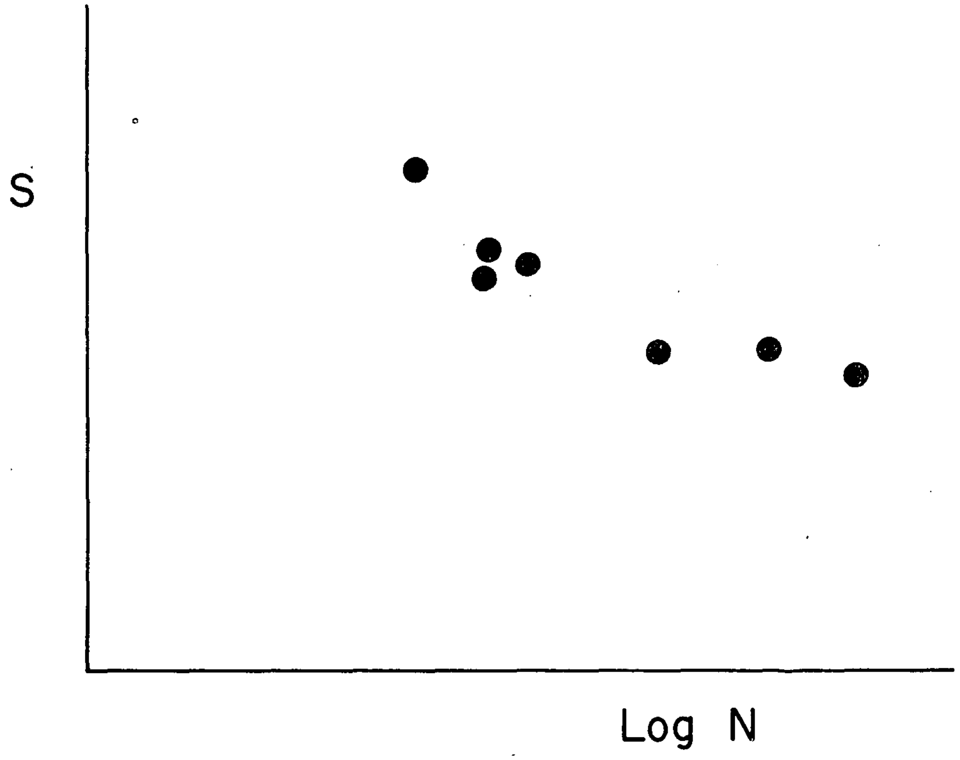

Fig. 10 Approximate Web Bending Stress Versus Cycles at Cracks

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