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EFFECT OF LARGE ALTERNATING STRAINS OF STEEL BEAMS

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SYNOPSIS

Small rolled structural steel cantilever beams were subjected to cyclic reversed loading. The maximum strain at the clamped end was carefully controlled and varied between ± 1.0 and ± 2.5 per cent. The behavior of these beams under repeated cycles of loading is reported in this paper. For the foregoing selected conditions the tendency for premature buckling of flanges is exhibited. This occurrence can be of significance in some cases of design.

INTRODUCTION

In the zones of the world where seismic activity is known to occur, it is necessary to design structures to resist dynamic forces caused by earthquakes; thus, it is necessary to select members and connections that can resist repeated and often completely reversed lateral loads. Somewhat analogous problems are also encountered in the design of off-shore structures for pounding by seas and to a certain extent in the design of structures to resist blast loadings. Despite the importance of the foregoing problems, the required experimental evidence for structural steel members and connections subjected to cyclically repeated loads does not seem to be readily available.

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The fatigue properties of steel have been studied rather extensively.[3,4,5] These studies, however, were usually done with applications to machine design in mind and principally explore the response of the material to a large number of loading cycles. The performance of many varieties of steel for such cases is well established.

In the low cycle fatigue range, which is of particular interest to the structural engineer who is concerned with prediction of mechanical behavior of structures in the inelastic range when these are subjected to fully or partially reversible loading conditions, the full potentialities of steel have not been thoroughly explored. Therefore, unless one is satisfied with limiting stresses to the elastic range, a number of questions remain open. One such question seems to be whether it is safe to base the predictions of low cycle fatigue behavior of rolled or fabricated members at large strains on cyclic twisting, bending, or tension-compression experiments with coupons. Some reliable experimental data are available for the latter.[6,7,8]

Based on the pilot experiments reported herein, it appears that for W F members subjected to repeated loads that induce large inelastic strains, local buckling—mainly in the flanges—may occur even after a few cycles and a different phenomenon than that involved in the low cycle fatigue of the material occurs. The number of cycles required to initiate local buckling appears to depend on the level of strain to which the critical section or region of the member is subjected. The initiation of local buckling gives rise to the development of large inelastic strains in the region where such local buckling occurs, and the induced strains seem to be highly detrimental to the endurance of the member. Therefore, the prediction of "low cycle fatigue endurance" of a structural member or of an entire structure in general cannot be based solely on the results obtained from experiments conducted to determine the low cycle fatigue properties of the material itself.

Undoubtedly numerous factors determine the low cycle fatigue endurance of a structural member. Among these, type and size of a member, states of stress and strain across and along the critical region of a member, the magnitude and history of the alternating strains, etc., may be important and should be considered. The experiments reported herein, however, were concerned only with the behavior of the same size cantilever beams made of small rolled steel section. These beams were subjected to repeated reversed loads that were controlled by the selected maximum strain at the clamped end of each

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3 Grover, H. T., Gordon, S. A., and Jackson, L. R., "Fatigue of Metals and Structures," Dept. of the Navy, Bureau of Aeronautics, U. S. Govt. Printing Office, Washington, D. C., 1960.

4 Gilligan, T. A., and England, T. R., "The Fabrication and Design of Structures of T-1 Steel," Proceedings, Highway Research Bd., Natl. Research Council, Washington, D. C., Vol. 39, 1960, pp. 86-102.

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6 Ludwik, P., "The Behavior of Metals Under Repeated Straining," Zeitschrift, Verein Deutscher Ingenieure, Berlin, Germany, Vol. 67, 1923, pp. 122-126.

7 Benham, P. P., and Ford, H., "Low Endurance Fatigue of Metals," Transactions of the Metallurgical Society, AIME, Vol. 215, pp. 794-807.

8 Benham, P. P. and Ford, H., "Low Endurance Fatigue of a Mild Steel and Aluminum Alloy," Journal of Mechanical Engineering Science, Vol. 3, No. 2, June, 1961, pp. 119-132.

beam. The maximum control strain of every cycle was kept constant throughout the series of cycles applied to each tested beam. In the experiments the maximum control strain was varied from 1% to 2.5%.

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EXPERIMENTAL ARRANGEMENT

In order to conduct this experimental investigation a special machine was designed and constructed; the general mechanical features of which are illustrated in Figs. 1 and 2. As may be seen from these figures, in a rigid steel frame made from channels, a provision was made for clamping an end of a cantilever beam. All of the beams tested were 4 by 4 M 13.0 having the cross section shown in Fig. 3.

The test specimens were cut from a long beam that was rolled from ASTM A7 steel and the average yield stress was 41 ksi. This property was deter-

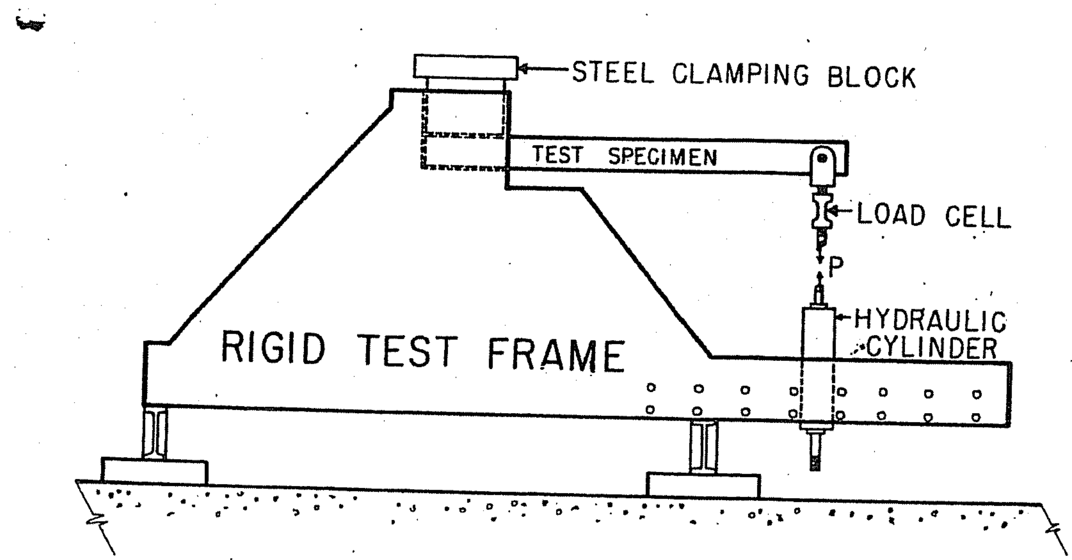

FIG. 1.—TESTING MACHINE

mined from tension tests performed on tensile coupons that were cut from the flanges and web of the beam.

The side view of a typical test specimen is shown in Fig. 4. To assure positive clamping of the end and to prevent longitudinal movement of the beam during the experiment, a 3/4-in. plate was welded to the end of the specimen which in turn was bolted to the machine frame.

The actual loads were applied by means of a double acting hydraulic cylinder shown diagrammatically in Figs. 1 and 5. The main features of the control system are shown schematically in the latter figure. A solenoid operated four-way hydraulic valve regulates the flow of oil into the loading cylinder. The solenoid is actuated by means of voltage controlled reversing switch. The signals received by the switch can be either from the loading cell or from the gages attached to the specimen at the edge of the clamping device. In the set of eleven experiments herein examined the strains at the clamped edge were used to control the machine cycles. For the repeated loading conditions in the inelastic range, the strain is considerably more sensitive than the mag-

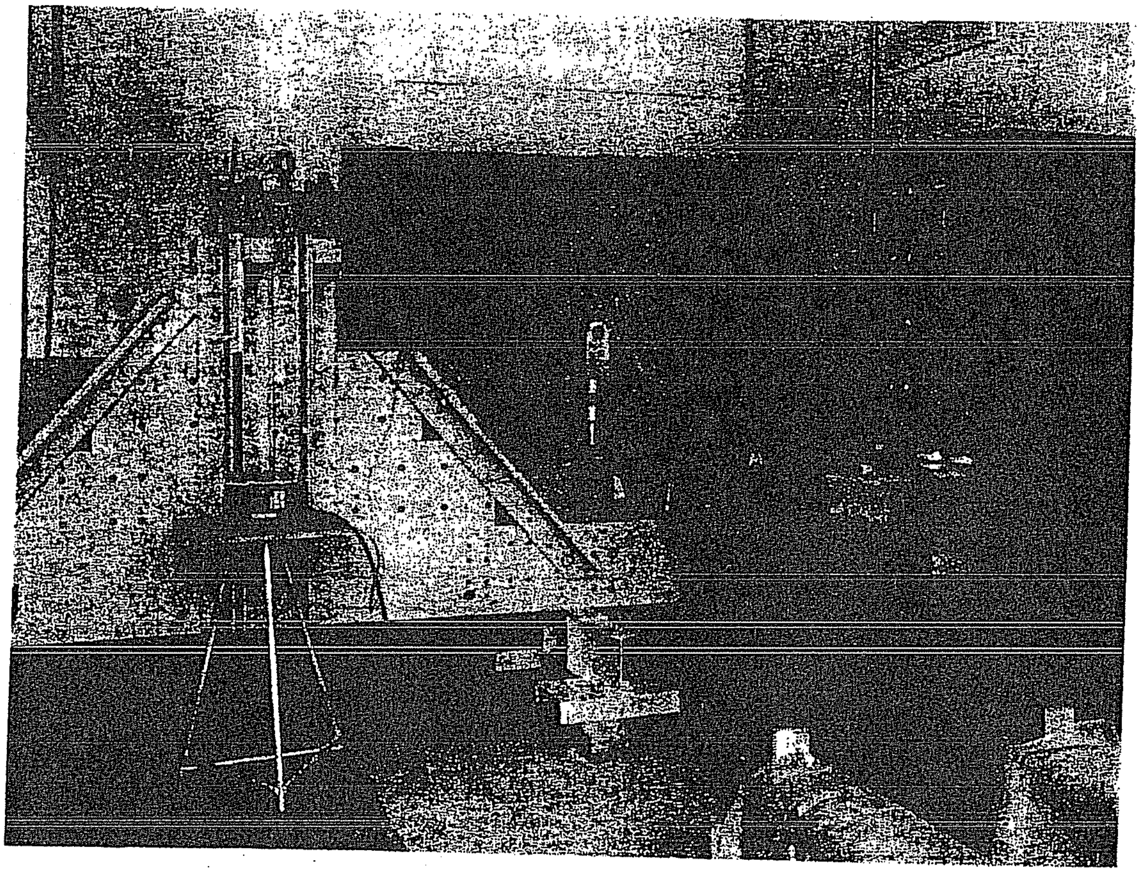

FIG. 2.—VIEW OF THE TEST SETUP

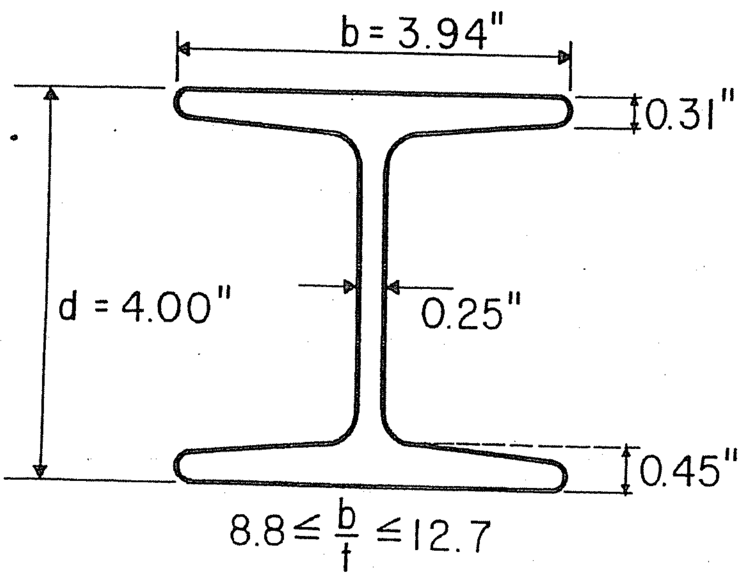

FIG. 3.—CROSS SECTION OF BEAM

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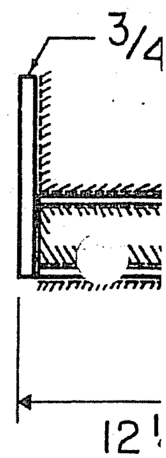

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The strains at the clamping device were usually measured by means of post yield electric strain gages. Some difficulties were encountered with the bonding of these gages to the specimens under repeated load applications. A specially designed clip gage (a modification of a gage used by Carlos Benito at the Central Laboratory of Madrid, Spain,), Fig. 6, was found more satisfactory in experiments in which a large number of load cycles were applied.

Direct writing oscillographic recorders provided continuous simultaneous information on the maximum strain, the magnitude of the corresponding applied load, and the end deflection of the specimens.

EXPERIMENTAL RESULTS

The number of cycles required to cause complete failure of the beams as a function of the controlling strain is shown in Fig. 7. The magnitude of the

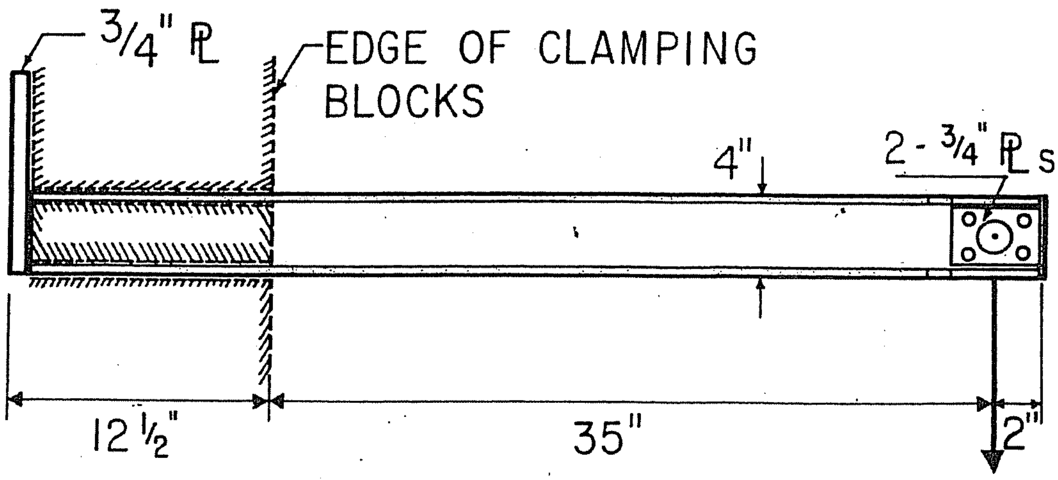

FIG. 4.—TEST BEAM

controlling strain, measured at the edge of the clamped end, varied from 1% to 2.5%. In each experiment the maximum controlling cyclic strain was kept constant for the specimen. When the maximum controlling cyclic strain was set at 1%, fracture of the beam occurred after 650 cycles. However, as soon as the controlling strain was increased, the fatigue life of the beams rapidly decreased as may be seen from the figure. For the specimen tested under a controlling strain of 2.5%, fracture occurred during the 16^{th} cycle.

The drastic drop in the low cycle fatigue endurance of the beams with increase in the magnitude of the controlling strain does not appear to be directly related to the deterioration of the mechanical properties of material itself at the clamped edge. Instead, the principal reason for this phenomenon can be attributed to the early development of local buckling in the beam flanges. The relationship between the number of cycles causing the initiation of local buckling of flanges in beams for various values of control strain is shown in Fig. 8. The shape of this curve greatly resembles that of Fig. 7 for failure of

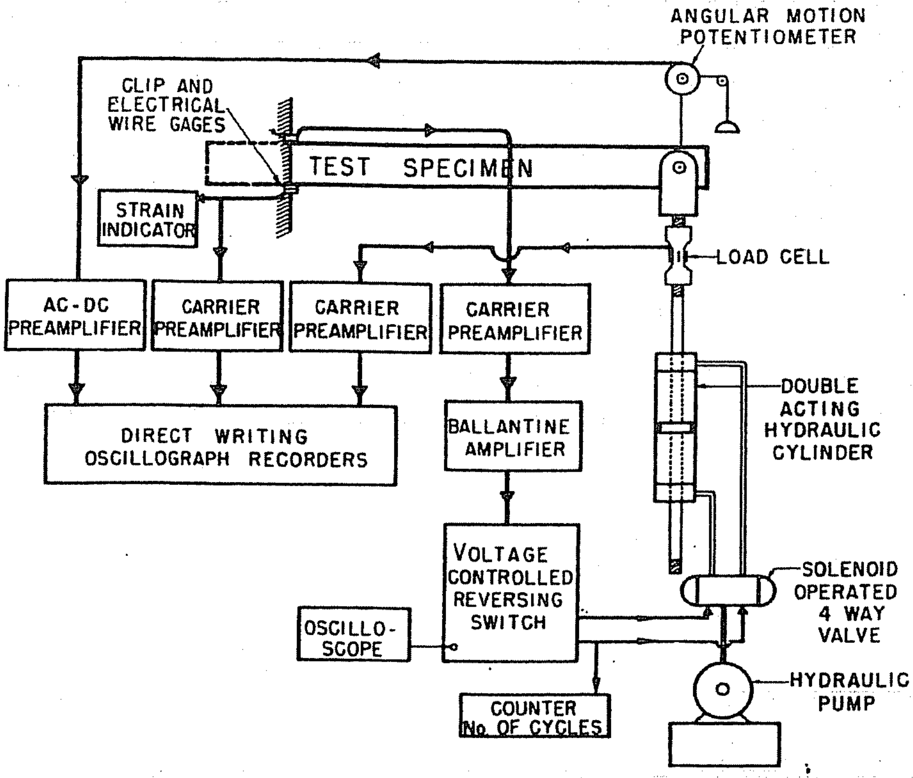

FIG. 5.—LOADING UNIT AND INSTRUMENTATION

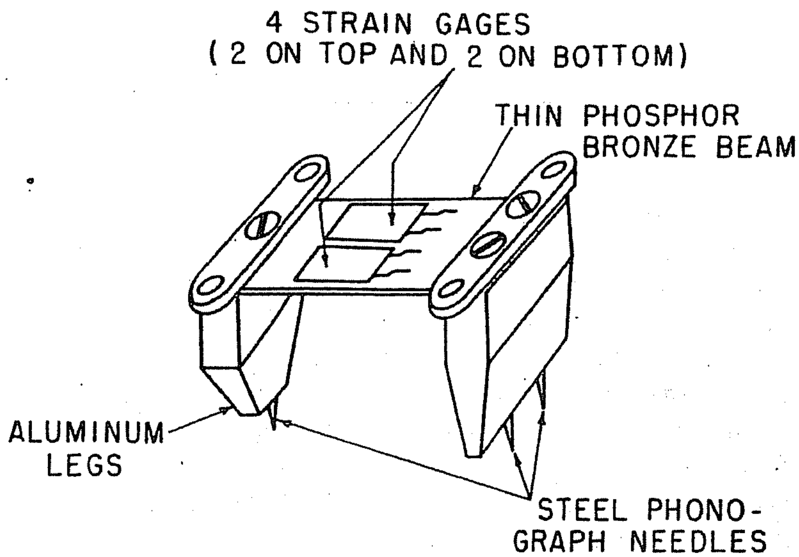

FIG. 6.—CLIP GAGE

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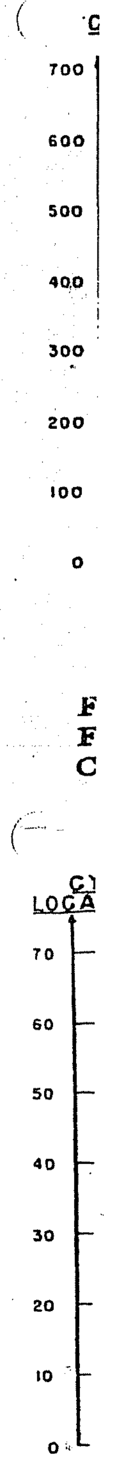

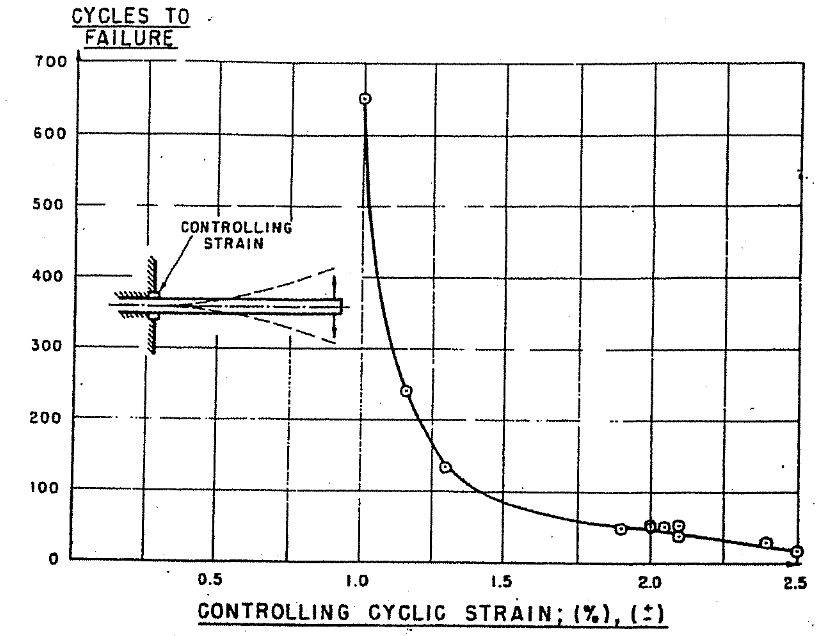

FIG. 7.—NUMBER OF CYCLES REQUIRED TO ATTAIN FRACTURE AS A FUNCTION OF THE CONTROLLING CYCLIC STRAIN

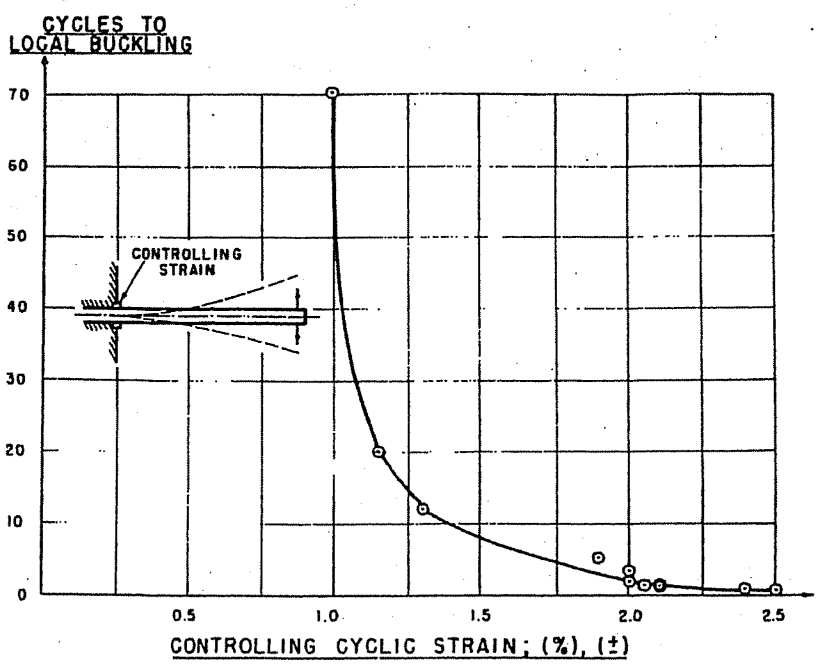

FIG. 8.—NUMBER OF CYCLES AFTER WHICH LOCAL BUCKLING OF FLANGES WAS DETECTED AS A FUNCTION OF THE CONTROLLING CYCLIC STRAIN

beams. It can be seen from Fig. 8 that at 1% controlling strain, local buckling was detected after 70 cycles. Initiation of local buckling was determined from visual observations, analysis of the record of deflection, and principally, from the record of strains obtained from electrical resistance wire gages placed along the flanges. Two of these gages can be seen in Fig. 13. With increasing controlling strain, local buckling was observed with fewer and fewer cycles. For the controlling strains greater than 2%, local instability was noted just after or during the first cycle.

The interesting appearance of the typical local buckling of flanges near the clamped end of a beam in an advanced stage of an experiment is shown in Fig.

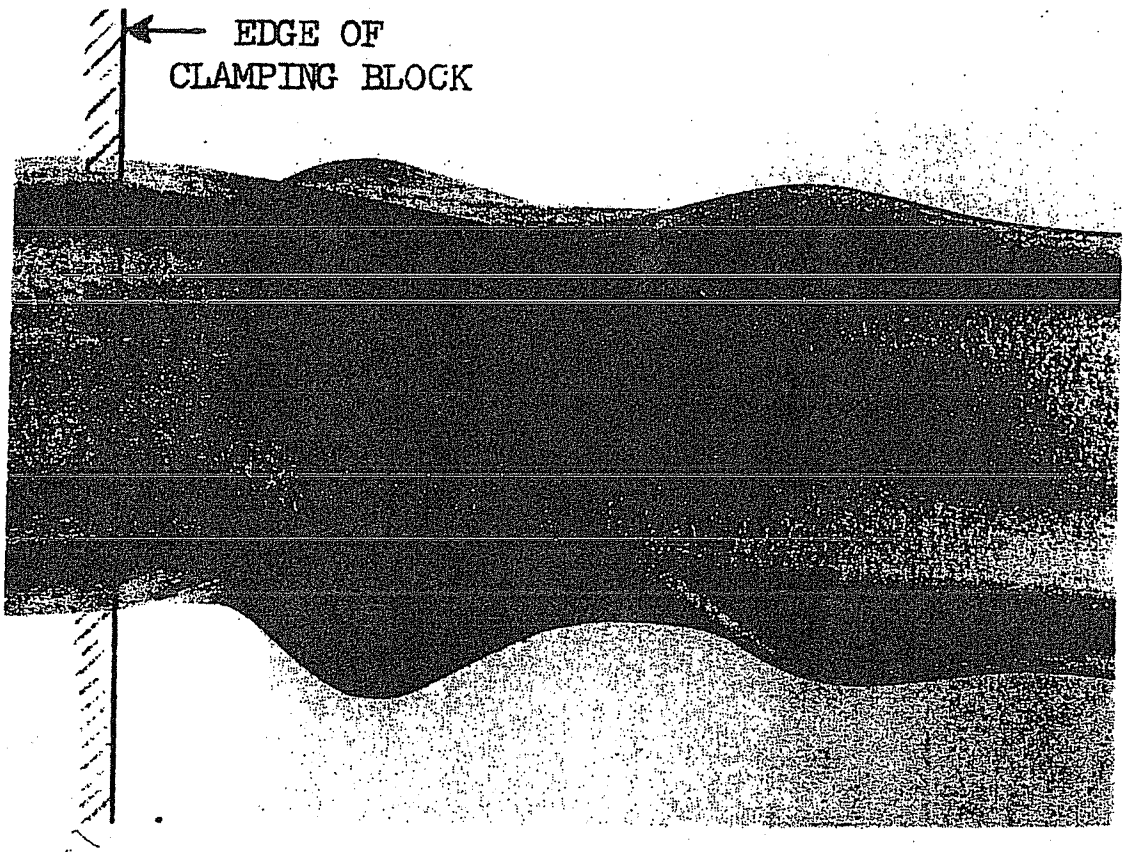

FIG. 9.—TYPICAL LOCAL BUCKLING OF FLANGES

9. The severe distortions of the flanges that are unsymmetrical with respect to the vertical plane through the longitudinal axis of the beam tend to induce torsional displacements of the section and local reductions in the flexural stiffness of the member which increased as the number of cycles increased. Unquestionably, these severe distortions of the flanges cause inelastic strains of magnitudes considerably larger than those of the controlling strains at the beam's clamped edge.

In all instances, except for 1% controlling strain, the strains induced in the distorted flanges caused the early formation of cracks that finally led to the fracture of the beam. The typical initiation of a fracture in the wrinkled flanges is shown in Fig. 10.

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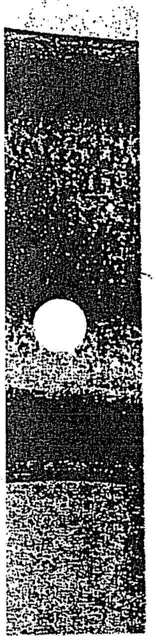

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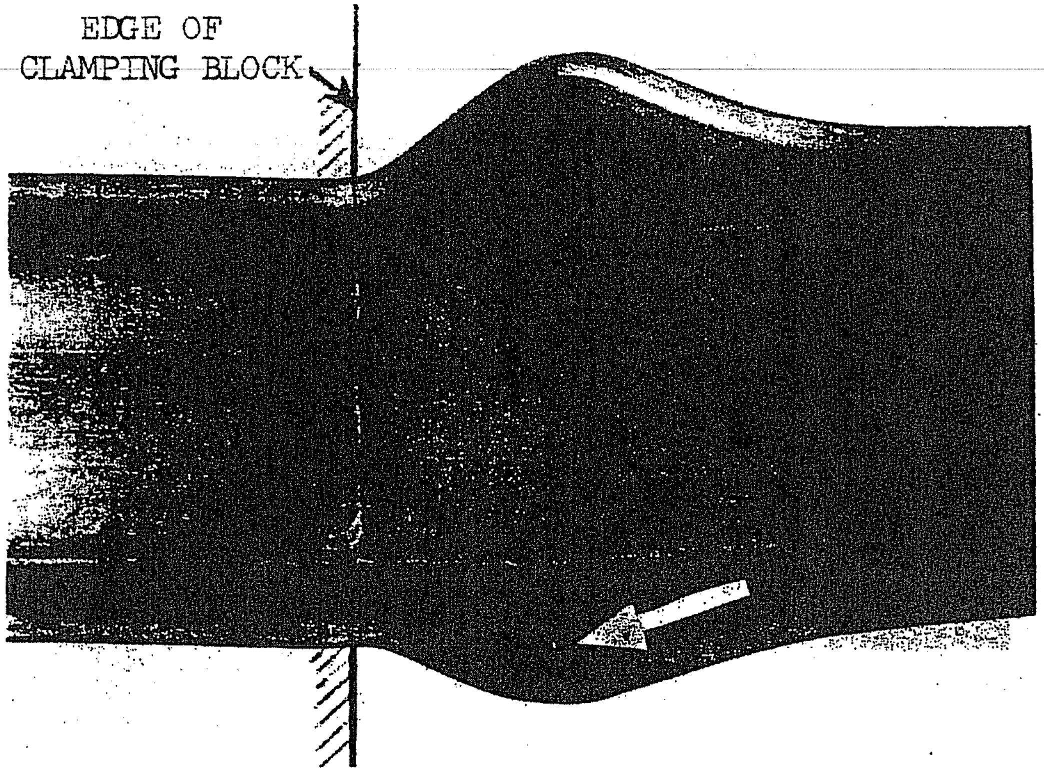

FIG. 10.—TYPICAL INITIATION OF FRACTURE

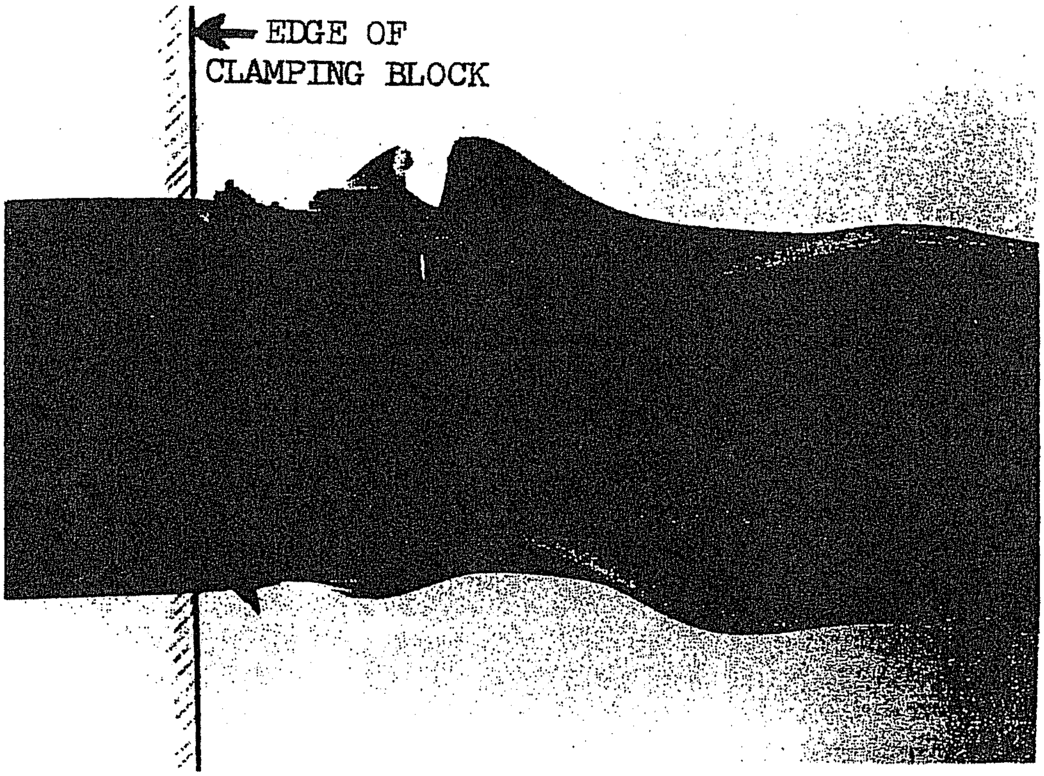

FIG. 11.—SPECIMEN NO. 10 AFTER TEST

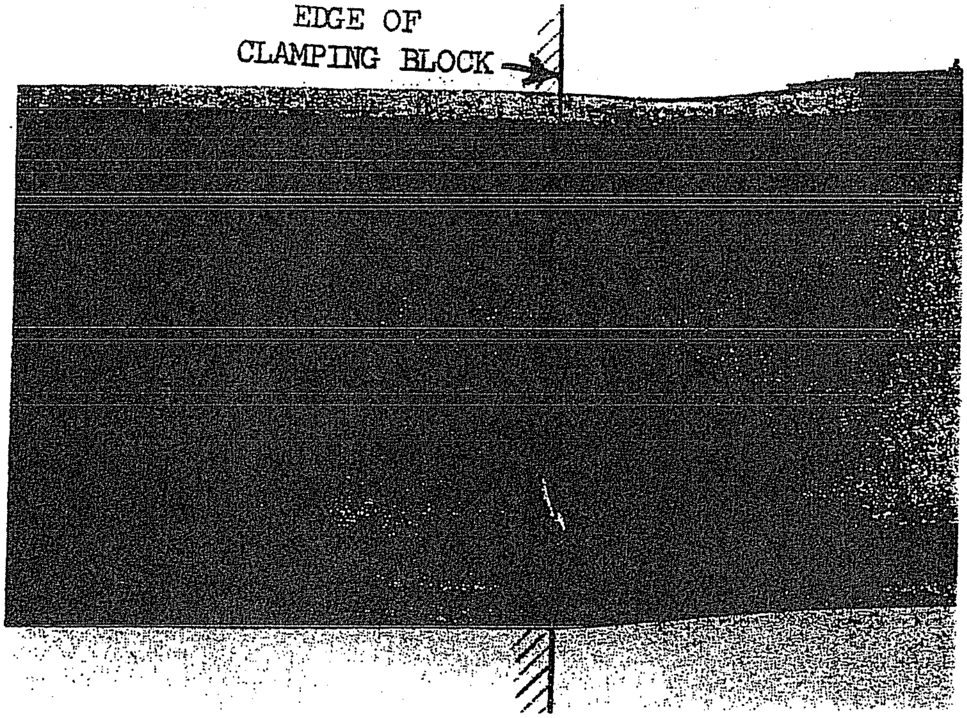

FIG. 12.—SPECIMEN NO. 7 AFTER TEST

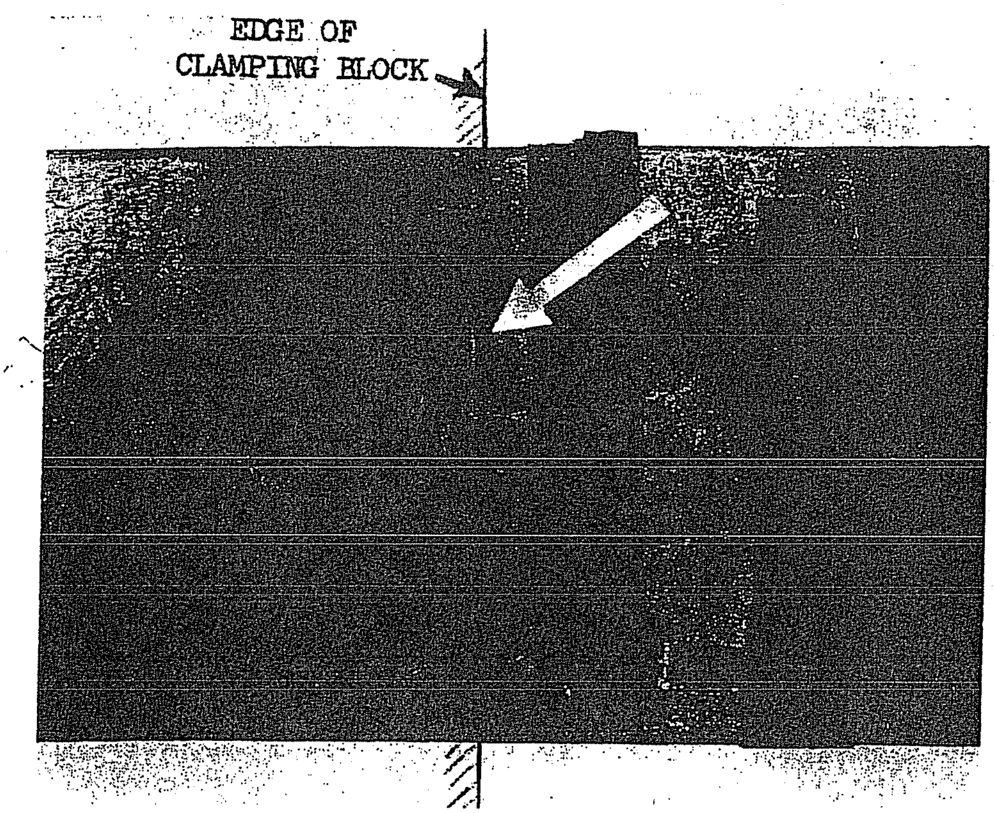

FIG. 13.—SPECIMEN NO. 7

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In the most extreme case of 2.5% controlling strains, buckling of flanges was observed during the second half of the first cycle. The wrinkles were enlarged considerably after each new cycle and the first crack became visible during the 9th cycle. Failure occurred during the 16th cycle and, as may be seen from Fig. 11, it was the result of the enlargement of the cracks in the wrinkles. It should be noted that no cracks were observed at the clamped section, which means that if local buckling of flanges had been prevented, the beam could have resisted a larger number of cycles under the same controlling strain.

In the experiment conducted with a controlling strain of ± 1.0% the first wrinkle in the flange was observed after the 70th cycle, but this wrinkle did not grow materially during the subsequent cycling. Only after approximately 500 cycles, first cracks appeared at the clamped section of the beam. A close-up view of the cracks is shown in Figs. 12 and 13. This beam failed by fracture, after 650 cycles, of the bottom flange across the clamped sections. No cracks were observed at the place where local buckling occurred.

EXAMINATION OF RESULTS AND CONCLUSIONS

The reported experiments must be considered as exploratory; only a few tests were conducted to date and it would be hazardous to formulate design criteria based on this work. However, some definite qualitative conclusions can be reached that appear plausible by examining the reported experimental results.

In low cycle fatigue of structural steel members at large strains, local buckling of flanges is of the utmost importance. It appears that in structural work involving repetition of fully or partially reversible loading conditions, the problem of preventing local buckling of elements is considerably more important than that which concerns the low fatigue endurance of the material itself. The presented experimental evidence clearly points in this direction. A comparison of the results obtained in this investigation with those obtained in the studies performed on low cycle fatigue endurance of steel seems to offer considerable support to the foregoing conclusion, For example, in the experiments with mild steel, Benham and Ford,[8] found that by strain cycling mild steel specimens between ± 2.43% strain, in tension and in compression, the number of cycles required to produce failure was greater than 400.

It is possible that in the reported experiments the initiation of local buckling of the flanges was precipitated by a particularly adverse combination of residual stresses and initial imperfections' this, however, is not particularly likely. The most plausible hypothesis for explaining the principal reason for the rapid deterioration in beam capacity is associated with the induced inelastic curvature of flanges. This curvature persists during the unloading process. In fact a kink remains even under zero load. The compressive and tensile forces, or both, which develop during the succeeding loading cycles, acting on the slightly kinked flanges of a beam, give rise to a force component that acts perpendicularly to the flange and further distorts the cross section. If the induced stresses are big enough, this distortion becomes plastic. Once this process begins, the wrinkle of the flange tends to become larger and larger as the number of cycles increases.

It is significant to note that in none of the eleven experiments was local buckling detected during the first half of first loading cycle. This was true even in the experiment with 2.5% controlling strain, which is higher than the strain at the onset of strain hardening of the material. Because the ratio of the flange width, b, to the average flange thickness, t, of the tested member was 10.5 (see Fig. 3), the results of this investigation may be considered to corroborate previous findings.[9] Based on the latter report, the recommendation is made[10] that the ratio b/t must not exceed 17 if premature local buckling of the flanges is to be prevented. This limiting ratio has been widely accepted.[11] However, because in the reported experiments local buckling occurred immediately after or even during the first complete cycle of the load application, the geometric proportions of the sections for reversing loads may have to be chosen more conservatively than those specifiec in the existing standards for static loads. It is clear that the guiding principle consists of either avoiding or at least delaying local buckling in steel members that may be subjected to inelastic alternating strains of large magnitudes.

For numerous structures, the actual loads may be approximated as static loads. In such cases, although in some complex structures the inelastic rotations required for full redistribution of moments may impose strains larger than 2.5%, the possibility of failure because of low cycle fatigue may be disregarded.[12,13] On the other hand, there are structures that must resist dynamic loadings and economy in design dictates that they must be designed for energy absorption capacity rather than strength. In these cases the selected ductility ratio may require the development of rather large strains. Although these strains may not exceed the ductility of the steel and local buckling may not take place during the first application of a large loading, such strains may be the cause of local buckling during the rebound of the structure or in subsequent cycles of energy inputs. The cumulative damage ultimately may deteriorate the toughness of the structure to such a point that failure may occur. Prevention of such failure is of great practical importance and further research in this field is needed before definite recommendations can be formulated.

WHY

ACKNOWLEDGMENTS

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