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The Behaviour of Steel Beams Under Slow Repeated Loading

Le comportement des poutres métalliques soumises à des répétitions de charge lentes

Das Verhalten von Stahlträgern unter langsam wiederholter Belastung

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Introduction

In the investigation described in this paper the load deformation relationship and the mode of failure have been determined for a series of mild steel flexural members subjected to slow repeated loading of sufficient magnitude to produce some degree of plasticity. Some tests have been carried out on plain bars but the greater number were on specimens with a weld at the centre of the span. The frequency of loading, namely 2000 cycles per day, closely corresponds to that adopted by BAIRSTOW [1]) in his classical series of tests on axially loaded specimens. In the early tests, commenced some years ago, work was confined to central concentrated loads applied to plain and welded specimens which had been cut out of the flanges of an 8 inch × 6 inch rolled steel joist. These early tests provided some guidance for a more recent programme, in which both plain and welded specimens are being loaded under central and two-point loads. As the mode of testing is slow, attention so far has been confined to tests under severe conditions in which the beams are loaded well beyond the yield moment. Ultimately it is intended to test additional specimens at lower loads to determine the effect of reducing the degree of overstrain.

Description of Tests

a) Testing Machine

The testing machine used for loading the specimens is shown in Fig. 1. The specimen, of rectangular cross section and 20 inch (50.8 cm) simply supported span, rests on knife edges on rollers and is loaded to bend about the major axis, by dead load, applied and removed by an overhead rocking beam. The motion of this rocking beam is actuated by an eccentric which is

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[1]) L. BAIRSTOW: "The Elastic Limits of Iron and Steel under Cyclical Variations of Stress." Phil. Trans. Roy. Soc., A. Vol. 210, 1909—1910, p. 35.

chain-driven from a 1000 to 1 reduction gearbox driven by a 1425 r.p.m. squirrel cage induction motor. The frame supporting the gearbox, motor and rocking beam is made independent of that supporting the specimen in order to isolate the specimen from any vibration which might develop.

An overload cutout is installed, to stop the motor in the event of any seizure of the equipment, and limit switches set below the specimen will stop the machine if the specimen deforms to an extent in excess of a selected maximum value. Locating stops are also provided to prevent the specimen from wandering whilst the test is in progress.

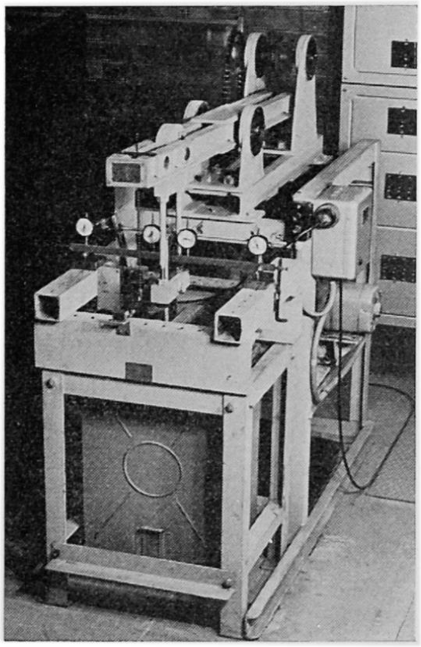


Fig. 1.

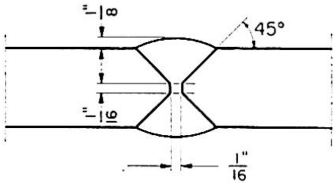


Fig. 2.

Deflections of the beams were recorded by four 0.001 inch dial gauges, mounted above the specimen supports and at points 2 inches from each side of the centre of the span. For the purposes of plotting graphs, the beam deflection was taken as the mean of the inner gauge readings minus the mean of the readings of the support gauges. A cycle counter of the manual reset type was fitted to operate from the rocker beam.

The cycle selected for these tests was such that the load was applied to the specimen for approximately 50% of the total time.

b) Specimens

In an early series of tests, the specimens were cut from the flanges of a length of 8 inch × 6 inch @ 35 lb./ft. British Standard rolled steel joist. The flanges were removed and one was oxy-cut into parallel strips, subsequently ground to provide specimens $^3/_4$ inch × $^1/_2$ inch (1.90 cm × 1.27 cm) in cross section. The second flange was divided transversely at the centre, double V butt-welded, and cut into specimens ground to the same section. These latter specimens proved to have been badly welded, and were used mainly for a pilot run on the machine. In addition a number of plain specimens were tested, some as static control specimens, some under repeated loading, and using a central concentrated load in both cases.

As it was felt desirable to study behaviour under conditions of pure flexure, two-point load spreaders were introduced and a second and more extensive series of tests was planned. In this case, specimens were cut from a piece of $^7/_8$ inch thick mild steel plate and both plain and welded specimens were prepared. For the latter, a 2′ 9″ length was taken, cut down the centre and prepared for welding. A double V-butt arc weld was made in accordance with Fig. 2, the first run being with a number 10 "Arcraft" E. M. F. electrode and subsequent runs with a number 8 electrode. These electrodes were claimed by the manufacturers to have the following properties:

Yield stress	=	25—27 ton/in.^{2}
Ultimate stress	=	32—36 ton/in.^{2}
Izod impact	=	45 ft.-lb.

Finally the plate was divided by flame cutting into thirty specimens. These were ground down to the dimensions of $^3/_4$ inch depth $\times$ $^1/_2$ inch width, the $^3/_4$ inch being in the direction of the thickness of the plate. The reduction of section in the last few passes of the specimens through the grinder was kept to a minimum in order to reduce the risk of severe work-hardening of the surface. It should be emphasised that the welding operation was carried out manually and no special care was taken to ensure freedom from defects. An X-ray of the weld revealed that the penetration had been complete but there was some evidence of a few small inclusions, and the presence of these was confirmed after the beams were tested and broken apart.

The welded specimens were subsequently tested with the weld at the centre of the span, under central or two-point loading. In the hope of improving the performance under repeated loading, a number of the welded specimens were normalised at 900° C for an hour prior to the final grinding process, and these also were ground carefully to the same surface finish as the other specimens. These specimens were subsequently tested under repeated central concentrated load.

Behaviour of Specimens

a) Static Tests

The details of the various specimens and results of static tests are summarised in Table 1. Typical curves plotted from these results are shown in Fig. 3. The value of full plastic moment accepted for the central point load tests was that corresponding to the point P (Fig. 3) at which the curve just entered the inclined region of strain-hardening behaviour. It will be seen that this value

Table 1. Static Test Results

Specimen Number	Type	Breadth b inches	Overall Depth $2d$ inches	Plastic Section Modulus $S=bd^2$ inches^3	Loading Condition	Load Corresponding to Full Plasticity lb.	Full Plastic Moment of Resistance M_p kip-in.	$\frac{M_p}{S}$ kip/sq. in.
FA 5	Plain	0.492	0.745	0.0681	Single point	500	2.50	36.8
P 2	Plain	0.502	0.751	0.0710	Two point	690	2.76	38.8
P 3	Plain	0.501	0.751	0.0708	Single point	540	2.70	38.2
W 1	Welded	0.502	0.752	0.0711	Single point	620	3.10	43.5
W 2	Welded	0.501	0.751	0.0708	Two point	715	2.86	40.5
W 19	Welded-normalised	0.467	0.726	0.0615	Single point	440	2.20	35.8

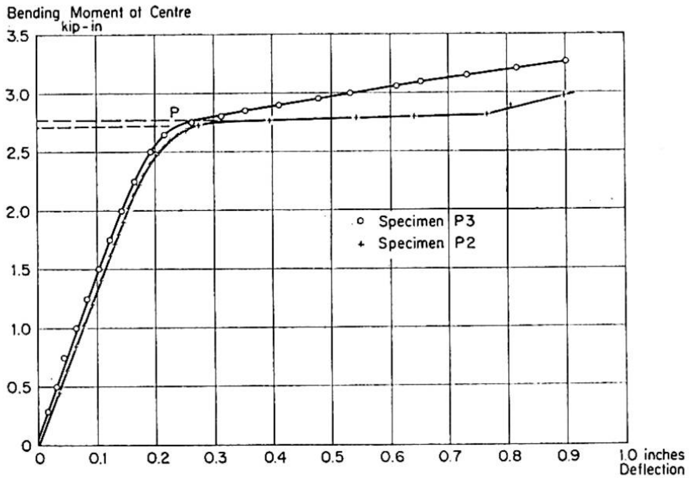


Fig. 3.

agreed fairly closely with that obtained from a uniform flexure test on the same type of specimen.

b) Tests under Repeated Loading

The results of the repeated loading tests, including details of the specimen dimensions, applied load and number of cycles to failure, are summarised in Table 2.

It will be observed that in all cases the loads applied to the specimen produced maximum moments exceeding that which on the basis of the simple plastic theory, would be expected to cause extreme fibre yielding, having in mind that no pronounced upper yield effects were observed in the static tests. Consequently in the loading of the specimens prior to repeated loading some creep occurred and continued until the first removal of the applied load. When the repeated loading was commenced, deformation increased rapidly in the first few cycles, but the rate of increase diminished considerably after about twenty applications of the load, and for the principal part of the test the incremental deflection with each cycle was extremely small.

After many cycles of load the final stage of each test was reached when a crack began to develop in the material. The first detectable sign of failure, both in the single and two point loading specimens, was the appearance of a fine transverse crack in the extreme tensile fibres near the centre of the span. This crack gradually penetrated into the material, until it progressed through approximately half of the depth of the section. This phase was accompanied by an initially slight, and ultimately rapid, increase in deflection under load, until the stage was reached when the machine was stopped by the tripping of the limiting switch. The machine was then readjusted and the loading continued until the specimen could no longer support the load and simply deformed in order to allow the loading bucket to follow the motion of the crosshead and overhead beam. The number of cycles was then recorded, and the test stopped; this stage was regarded as failure of the specimen.

The final phase of crack propagation developed over many cycles of loading, and in some cases, over a period of some months. At no time did any specimen develop brittle characteristics and snap catastrophically and in many cases the specimens carried the full load even when the crack had penetrated through more than half the depth of the specimen. Even when the tests were abandoned, some slight elastic recovery of each specimen was observed when the bucket and beam were raised.

It is convenient to represent the readings of progressive deflection against the number of cycles, as shown in Fig. 4, using a logarithmic scale as abscissa, and linear scale for ordinates. The graphs as shown are at arbitrary heights but the true initial values of deflection at the commencement of testing are given in Table 2.

Table 2. Repeated Loading Test Results

Specimen Number	Type	Breadth b inches	Overall Depth $2d$ inches	Plastic Section Modulus $S = bd^2$ inches^3	Loading Condition	Full Plastic Moment M_p kip-in.	Applied Repeated Load lb.	Corresponding Maximum Moment M kip-in.	$\frac{M}{M_p}$	$\frac{M}{S}$ kip/sq. in.	Number of Cycles to Failure	Initial Value of Deflection inches
FA 1	Plain	0.492	0.745	0.0681	Single point	2.50	460	2.30	0.92	33.7	3,689,392 +	0.1504
FA 5	Plain	0.492	0.745	0.0681	Single point	2.50	520	2.60	1.04	38.1	382,265	0.2997
P 5	Plain	0.500	0.750	0.0703	Two point	2.74	700	2.80	1.02	39.8	109,884	0.6080
W 16	Welded	0.500	0.750	0.0703	Single point	3.06	624	3.12	1.02	44.5	29,245	0.3788
W 25	Welded	0.505	0.750	0.0711	Single point	3.10	593	2.96	0.96	41.7	56,842	0.2564
W 3	Welded	0.502	0.751	0.0709	Single point	3.09	572	2.86	0.93	40.5	50,557	0.1974
W 12	Welded	0.501	0.751	0.0708	Single point	3.08	530	2.65	0.86	37.5	161,632	0.2137
W 6	Welded	0.501	0.751	0.0708	Two point	2.86	700	2.80	0.98	39.6	21,852	0.5172
W 5	Welded	0.501	0.751	0.0708	Two point	2.86	665	2.66	0.93	37.7	71,014	0.2816
W 15	Welded	0.501	0.750	0.0705	Two point	2.85	630	2.52	0.89	35.7	63,332	0.2225
W 26	Welded	0.500	0.750	0.0703	Two point	2.84	595	2.38	0.84	34.0	108,331	0.1801
W 19	Welded, normalised	0.467	0.727	0.0616	Single point	2.20	440	2.20	1.00	35.8	16,561	0.2024
W 20	Welded, normalised	0.467	0.727	0.0616	Single point	2.20	418	2.09	0.95	33.9	18,455	0.1549
W 22	Welded, normalised	0.467	0.727	0.0616	Single point	2.20	396	1.98	0.90	32.2	31,661	0.1481

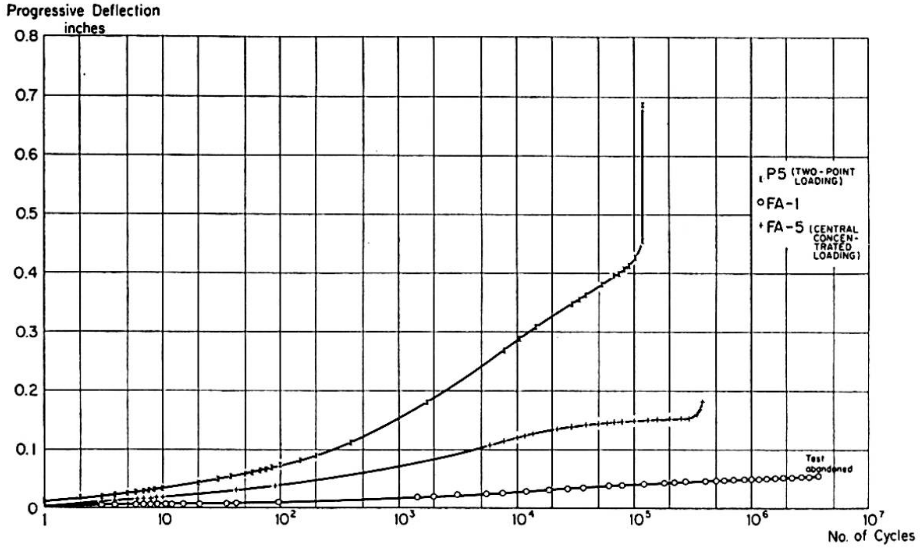


Fig. 4a.

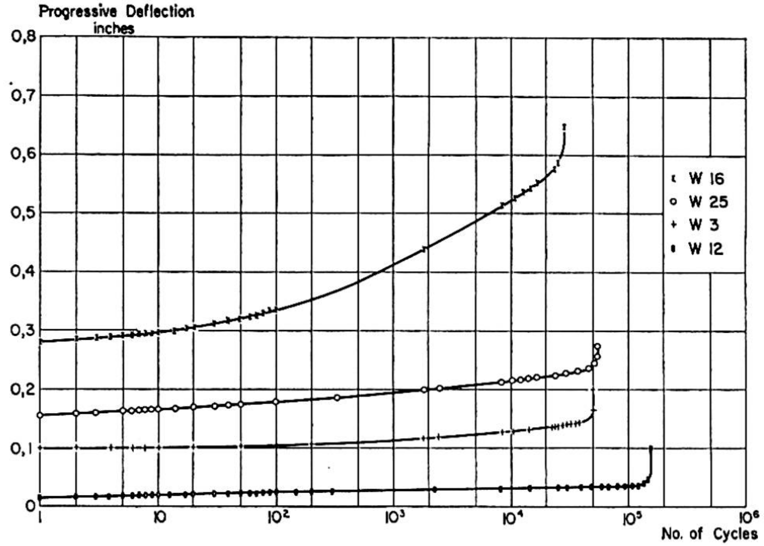


Fig. 4b.

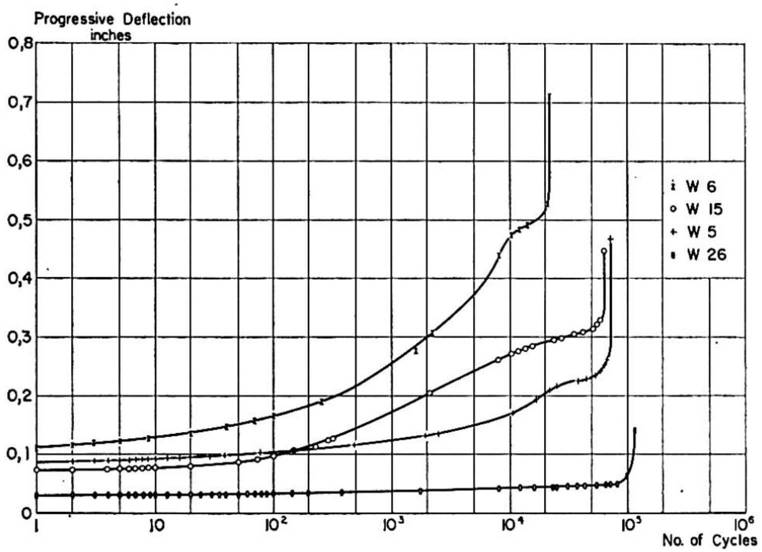


Fig. 4c.

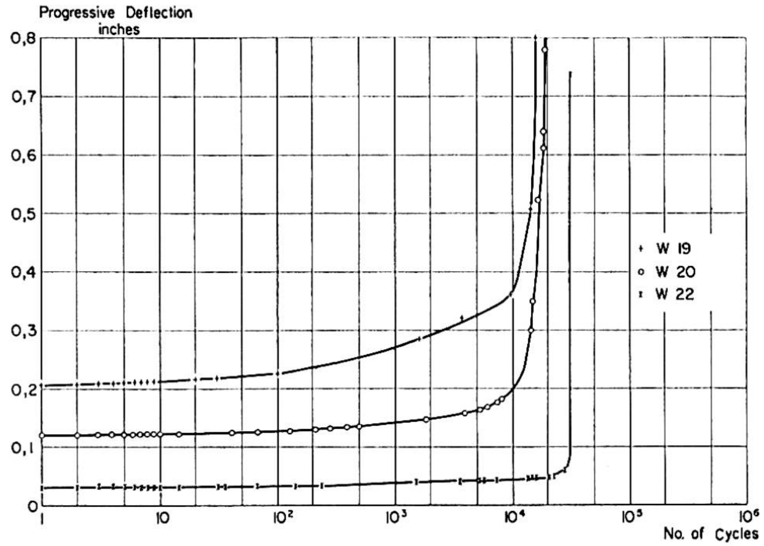
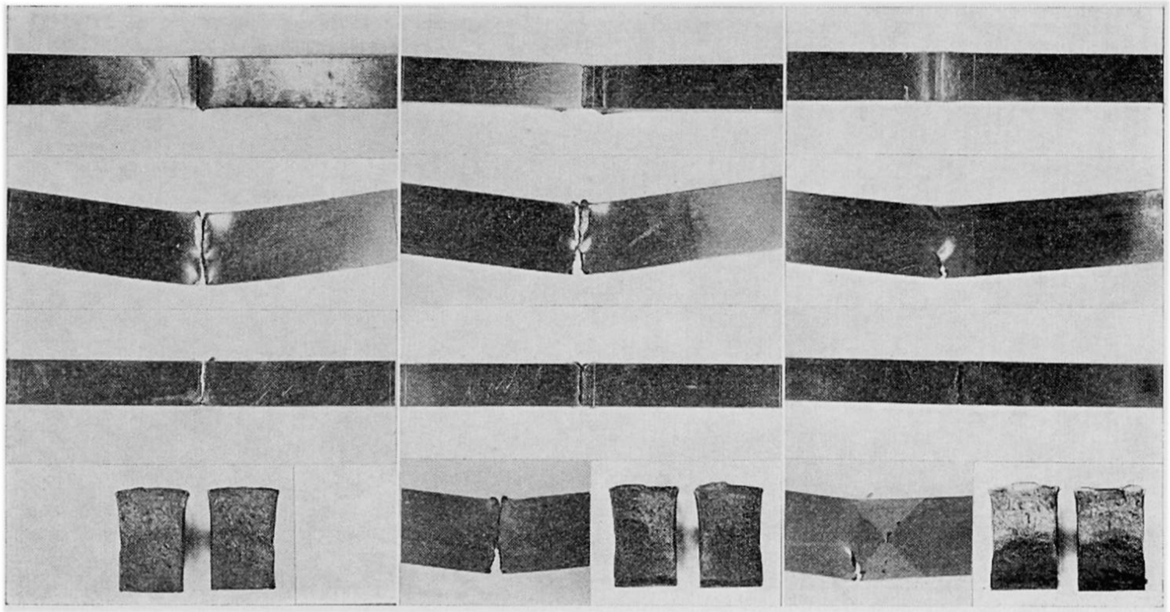


Fig. 4d.



top view

side view

bottom view

fracture	side view after etching	fracture	side view after etching	fracture

Specimen FA-5 — Fig. 5a.

Specimen W 20 — Fig. 5b.

Specimen W 15 — Fig. 5c.

In a number of the tests, readings were taken of the beam deflections both when the load was applied and when it was subsequently removed. These can be plotted as two curves, the vertical intercept between which was found to be constant throughout each test, suggesting that at all stages the recovery was elastic. For a beam of linear and elastic material, the magnitude δ would be given by the expression

$$\delta = \frac{472\,P}{3\,E\,I}$$

in inch units, for the central load tests, and by

$$\delta = \frac{448\,P}{3\,E\,I}$$

for the two point loading tests, where P, E and I are respectively the applied load, elastic modulus and second moment of area of the testpiece. The values of E, as derived from these expressions and using the test results, ranged between 27.3×10^6 p.s.i. and 30.8×10^6 p.s.i., so that in each case the magnitude of the recovery can be said to agree satisfactorily with that expected on the basis of linear elastic behaviour.

Nature of Fractures

A number of photographs of specimens after testing showing elevations, top and underneath views and fracture surfaces are shown in Fig. 5. It will be evident that in all cases the region of the specimen adjacent to the fracture underwent considerable plastic deformation, and this was accompanied by lateral flow of the material, resulting in the large distortions of the cross-sections. The distorted surfaces are also clearly seen in the elevations. In a number of specimens rippling of the compression face was evident, and in others, some fine transverse cracks could be observed in the compression face when the specimen was closely examined. It will be observed from the photograph of specimen W 20 (Fig. 5b) that, even when the specimen was broken apart prior to photographing, there was some ductility of the remaining material as the two parts do not mate together precisely at the top.

Under single point loading conditions, the cracks were located at a section near the centre, but in most cases displaced approximately $^1/_2$ inch away and near the extremity of the welded zone. In the case of the welded specimens subjected to two point loading, the cracks again frequently developed to one side of the centre line of the span, as is shown in Fig. 5c. (Specimen W 15.) The unwelded specimen subjected to two point loading developed a crack which originated under one of the loading points, in the tensile fibre. The crack propagated from one of the scribed lines used for marking out the specimen prior to testing. Cracks in the specimens propagated vertically, and often appeared to emanate from a small weld defect such as an inclusion near the tensile face. It will be seen from the photographs in Fig. 5 which show elevations of typical welded specimens after etching with 10 per cent nitric acid in methylated spirit, that the cracks all originated within the welded zone, although in many cases they subsequently penetrated regions of unwelded material.

If attention is directed to the sectional views, which were taken after the specimens were broken apart in a vice, it will be observed that in some striations occurred consistent with the progressive nature of the cracking. These are particularly noticeable in the case of specimen FA-5. The fractures were crystalline in appearance, the lighter colour occurring in the region which was freshly broken.

Life of Specimen as a Function of Loading

The test results are summarised in Fig. 6. Here, the number of cycles to failure are plotted on a logarithmic axis, against the applied maximum moment divided by the plastic section modulus of each specimen. These same results are plotted again in Fig. 7, the ordinate being the maximum applied moment divided by the full plastic moment of a specimen of the same dimensions, as determined from the static tests. In both figures the relationship between the logarithm of the life of a specimen, and loading, will be seen to be sensibly linear.

It will be observed that the curves for two point and central point loading specimens agree fairly closely, when allowance is made for the different values of full plastic moment of resistance. If it is assumed that the section where

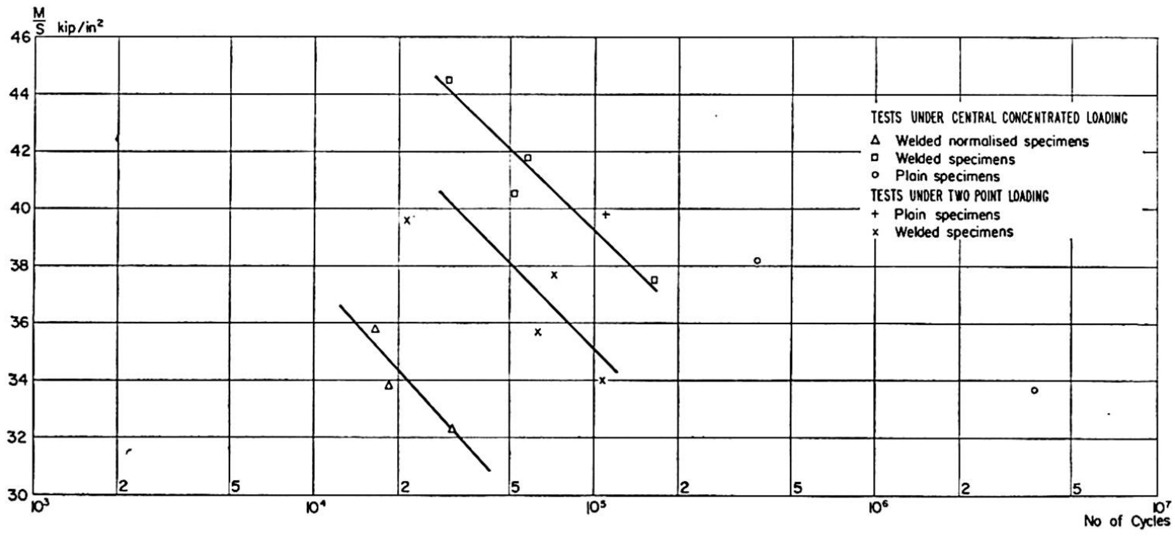


Fig. 6.

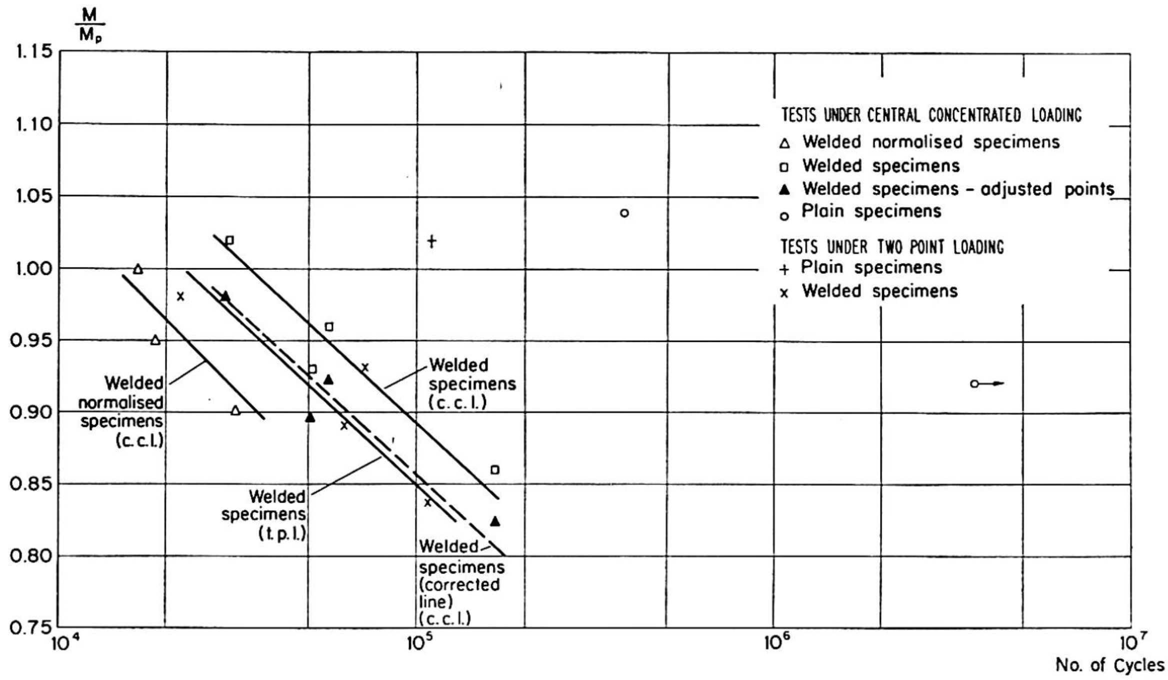


Fig. 7.

cracking occurs is at the extremity of the weld as is suggested by the photographs of the etched specimens, it will be seen that at these sections, the moment is only 96 per cent of the central moment, consequently the curve in Fig. 7, for the welded central load tests will be displaced downwards to the position shown by the broken line. The results of the central load and two-point load tests then agree very closely.

It is also interesting to note that, while the process of normalising the welded specimens lowered the yield point of the material their life appeared to be slightly reduced.

Conclusions

Although at this stage, any conclusions must be regarded as a little tentative, the tests to date have given a great deal of qualitative information on the behaviour of steel members under many cycles of slow repeated loading, and it is hoped that further work will enable the relationship between the applied moment and life of the specimen to be determined over a wide range of moments.

It can be said, however, that the material does not behave in a brittle manner with little plastic deformation during the course of repeated loading, and catastrophic collapse does not take place. Even when testing was discontinued and the specimens were withdrawn from the machine and broken in a vice, they exhibited some residual ductility. In addition, though there were some imperfections in the welding of the specimens tested, these did not lead to collapse of the specimens at a very early stage.

As has been mentioned, it is planned in future testing, to extend the range of applied moments to include both high values well into the strain-hardening range, and lower values closer to the yield moment, and to conduct tests on specimens having close control on the material and welding, under intermittently applied, and reversing moment, and under programmed loading.

Acknowledgements

The Authors acknowledge the assistance of Messrs. J. J. Reilly and R. Kwan, students in the Department of Civil Engineering, University of Sydney, who conducted a number of the tests as part of an undergraduate thesis exercise.

Summary

An account is given of a series of preliminary tests on rectangular, simply supported mild steel beams subjected to many cycles of intermittent transverse loading, applied at $1\,^1/_2$ cycles per minute. The results suggest that the life of a specimen as plotted on a logarithmic scale, bears a linear relationship to the applied moment. The behaviour of both plain and welded specimens is described, both prior to, and after the development of cracking.

Résumé

Les auteurs présentent une série d'essais préliminaires exécutés sur des éprouvettes fléchies en acier doux, de section rectangulaire et simplement appuyées, soumises à un grand nombre de cycles de chargements transversaux discontinus appliqués à raison de $1\frac{1}{2}$ cycle par minute. Il ressort des résultats que le nombre de cycles supporté par l'éprouvette, si on le rapporte à une échelle logarithmique, peut s'exprimer linéairement en fonction du moment appliqué. On décrit le comportement d'éprouvettes ordinaires et d'éprouvettes soudées avant et après le début de la fissuration.

Zusammenfassung

In einer Reihe von Vorversuchen wurden einfach gelagerte Prüfstücke aus St 37 mit rechteckigem Querschnitt einer großen Zahl von intermittierenden Lastwechseln auf Biegung mit $1\frac{1}{2}$ Perioden pro Minute unterworfen. Die Versuche ergaben einen linearen Zusammenhang zwischen den auf einer logarithmischen Skala aufgetragenen Lastwechseln, die vom Prüfstück ausgehalten wurden, und dem belastenden Moment.

Der Bericht umfaßt das Verhalten von gewöhnlichen und von in Feldmitte geschweißten Prüfstücken, vor und nach dem Anriß.