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Post-Buckled Behaviour and Incremental Collapse of Webs Subjected to Concentrated Loads

Comportement post-critique de voilement et ruine des âmes soumises à des charges concentrées

Überkritisches Beulverhalten und zusätzlicher Kollaps von Stahlblechen infolge konzentrierter Lasten

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1. Introductory Remarks

After the completion of the investigation into the post-buckled behaviour of webs in shear, which was conducted partially by K.C.Rockey and the first of the authors in Swansea and Cardiff /1/ and partly, after the return of the author to Czechoslovakia, at the Institute of Theoretical and Applied Mechanics in Prague /2/, a new research project was started. This deals with the influence of flange stiffness upon the ultimate load behaviour and incremental collapse of thin webs subjected to a concentrated (or, more accurately, to a narrow partial edge) load. The investigation is carried out by a research team that consists of the first of the authors, Ing.Drdácký, Ing.Kratěna, Ing.Zörnerová (all of them from the Institute of Theoretical and Applied Mechanics in Prague), the other author and Ing.Bohdanecký (both from the Structural Institute in Prague). The objective is to obtain (together with other investigators /3/, /4/, /5/) enough information about the ultimate load behaviour of plate girders the webs of which are subjected to a patch load, such as are crane run-way girders, certain types of bridge girders and similar structures.

2. Test Girders

Two series of test girders were tested. The general details of the test girders of the first series are given in Fig. 1a, the corresponding dimensions (in mm) in Table 1a. The details of the second series girders are shown in Fig. 1b, and the dimensions in Table 1b.

An inspection of the figures shows that the test girders of the second series had two web panels. Each of them was tested individually, the supports being positioned under the boundary vertical stiffeners of the panel. Web panel W 2 was tested first, the girder being subjected to a static load.

Table 1a

Girder	Loading	Web: Depth b [mm]	Web: Thickness t [mm]	Web: $\frac{b}{t}$	Flange: Width b_f [mm] Upper	Flange: Width b_f [mm] Lower	Flange: Thickness t_f [mm] Upper	Flange: Thickness t_f [mm] Lower	Flange: I_f/a^3t [Units of 10^{-6}] Upper	Flange: I_f/a^3t [Units of 10^{-6}] Lower	P_{cr}^{RB} [T]	P_{ult} [T]
PTG 1	static						5.95	5.95	3.48	3.48	2.78	3.6
PTG 2	static				50	50	5.97	5.93	3.50	3.43	2.2	4.0
PTG 3	cyclic						5.09	5.03	2.17	2.09	2.38	5.0
PTG 4	cyclic						5.08	5.06	2.16	2.13	2.79	4.6
PTG 5	static						16.21	16.14	63.89	63.07	2.53	5.5
PTG 6	cyclic	500	2	250	45	45	16.24	16.14	64.25	63.04	2.53	5.5
PTG 7	cyclic						16.17	16.07	63.48	62.31	2.52	5.6
PTG 8	static						16.25	16.11	64.36	62.72	2.53	5.5
PTG 9	cyclic						24.25	24.78	237.68	253.60	2.83	7.2
PTG 10	cyclic				50	50	24.64	24.24	249.33	237.38	2.83	7.0
PTG 11	static						24.80	24.84	254.22	255.45	2.84	7.5
PTG 12	static						24.40	25.00	242.11	260.42	2.85	8.0

Table 1b

Girder	Web	Loading	Web: Depth b [mm]	Web: Thickness t [mm]	Web: $\frac{b}{t}$	Flange: Width b_f [mm] Upper	Flange: Width b_f [mm] Lower	Flange: Thickness t_f [mm] Upper	Flange: Thickness t_f [mm] Lower	Flange: I_f/a^4 [Units of 10^{-6}] Upper	Flange: I_f/a^4 [Units of 10^{-6}] Lower	P_{cr}^{RB} [T]	P_{ult} [T]
TG 1	W1	cyclic						5.50	5.18	0.887	0.741	2.2	6.5
	W2	static				160	160						5.0
TG 1'	W1	cyclic						5.42	5.56	0.849	0.917		
	W2	static											
TG 2	W1	cyclic						10.09	10.08	6.85	6.83	2.24	7.0
	W2	static											6.5
TG 3	W1	cyclic	1000	2.5	400	200	200	16.24	16.15	28.55	28.08	2.36	9.2
	W2	static											7.0
TG 4	W1	cyclic						20.17	20.12	54.70	54.30	2.48	9.8
	W2	static											9.0
TG 5	W1	cyclic						30.88	30.44	245.39	235.05	2.78	18.0
	W2	static				250	250						18.0
TG 5'	W1	cyclic						30.50	30.48	236.44	236.00		
	W2	static											

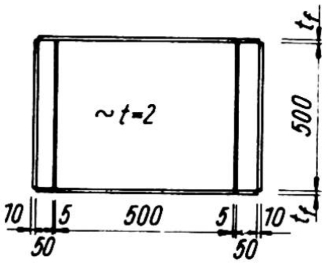

Fig. 1a

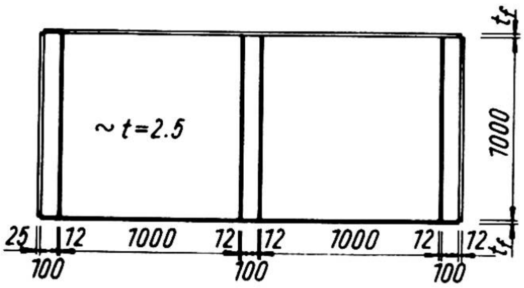

Fig. 1b

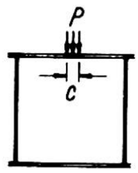

Fig. 2

Then this web panel was cut off, and web panel W 1 was subjected to a cyclic load.

All web panels in both aforesaid series had aspect ratio α of 1. Test girders with other α -ratios will be tested in 1972. In each series the depth-to-thickness ratio $\lambda = b/t$ of the web was constant, but the flange dimensions varied from girder to girder, so that the effect of the flexural rigidity of flanges upon the ultimate load behaviour of webs could be studied.

The research on steel girders was accompanied by a photoelasticity investigation conducted by the first of the authors and J.Kratěna on reduced-scale epoxy-resin models.

In all tests the web panels were subjected to a narrow partial edge load, applied on to the upper flange at the mid-distance of the vertical stiffeners. The width of the load c = a/10 (in one case c = a/5), a denoting the width of the web panel (Fig.2).

3. Apparatus

A description of the experimental apparatus and of the programme of measurements was the objective of the paper /6/ presented by the authors at the Congress of RILEM in Buenos Aires. For this reason only a brief information about the apparatus will be given in this publication, the aim of which is to discuss main test results.

The buckled pattern of the web was measured by means of a stereophotogrammetric method /7/. The application of this method was advantageous in the aforesaid tests, since it enabled the authors to take all readings in a very short time moment (0,001 sec.). This was desirable in the static load tests (because a study of the final, plastic, stage - in which the web and flanges were already yielding - was one of the main objectives of the investigation) and indispensable in the cyclic load tests (in which the web and flanges were "breathing").

A special device, designed by P.Pašník, enabled the authors to take deflection readings at a given moment of loading cycles; for example, when, in a "breathing" cycle, the web deflection attained its maximum (amplitude) value. Moreover, the stereophotogrammetric method made it possible to measure not only the deflection perpendicular to the web, but also the in-plane distortion of the mesh that was marked on the web, and the deformation of the boundary frame of the web panel.

A set of strain gauges was attached to both sides of the web and of the upper flange in order the stress pattern in the girder could be studied. Several of the strain gauges, as well as two deflection pick-ups, were linked to an automatic recorder "Ultralette". Thus it was possible to study, as a function of time, the progression of the plastification of the girder in the static load tests and the deflection (and strain) stability in the cyclic load ones.

The post-failure plastic residue in the web and flanges of each test girder was also carefully measured.

4. Static Load Tests

The first part of the investigation was concerned with the post-buckled behaviour of webs subjected to a static patch load. The influence of the flexural rigidity of flanges upon the buckled pattern and stress state in the web and flanges, and upon the ultimate load of the whole girder was studied.

The post-failure plastic residues w_{pl} in web panels W 2 of test girders TG 1 (flexible flanges) and TG 5 (rigid flanges) are plotted in Figs. 3a and b. The plastic residues in the upper (i.e. loaded) flange of girders TG 1, TG 3 and TG 5 are given in Fig. 3c. A photo of the collapsed girder TG 4 is shown in Fig. 3d.

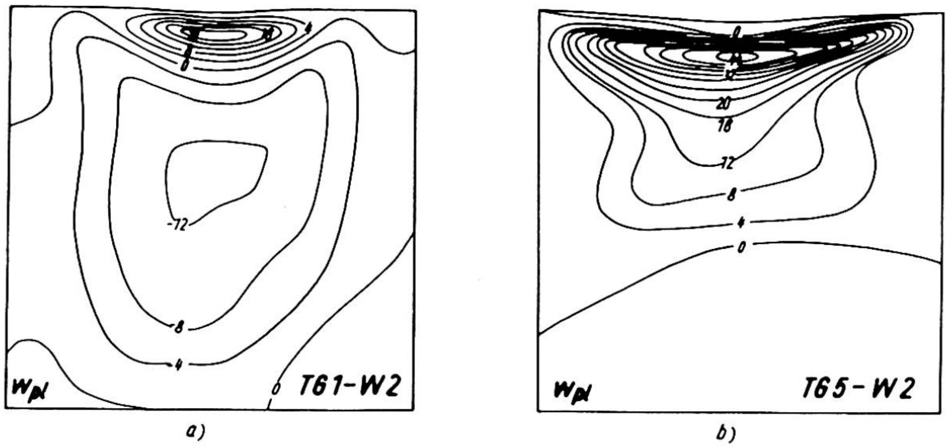

Fig.3

An inspection of the aforesaid figures shows the pronounced influence that flange stiffness has on the deformation of the test girder. While, in the case of flexible flanges, the buckling of the web and the deflection of the flanges are localized in the neighbourhood of the partial edge load, for heavy flanges the buckled pattern of the web and the flexure of the flange are distributed almost over the whole width of the web panel. The performance of the web panel is then more homogeneous; this affecting – as it will be demonstrated below – very beneficially the ultimate load behaviour of the girder.

The pattern of ε_{my} (ε_{my} denoting the vertical – i.e. parallel to the load – membrane strain) in web W 2 of girder TG 1 (flexible flanges) is given in Fig. 4. Fig. 4a shows the values of ε_{my} along two horizontal lines (the first of them being situated 30 mm and the other 300 mm from the top flange), and Fig. 4b gives the strains ε_{my} along the vertical axis of the web. The bending strains ε_{bx} in the upper (i.e. loaded)

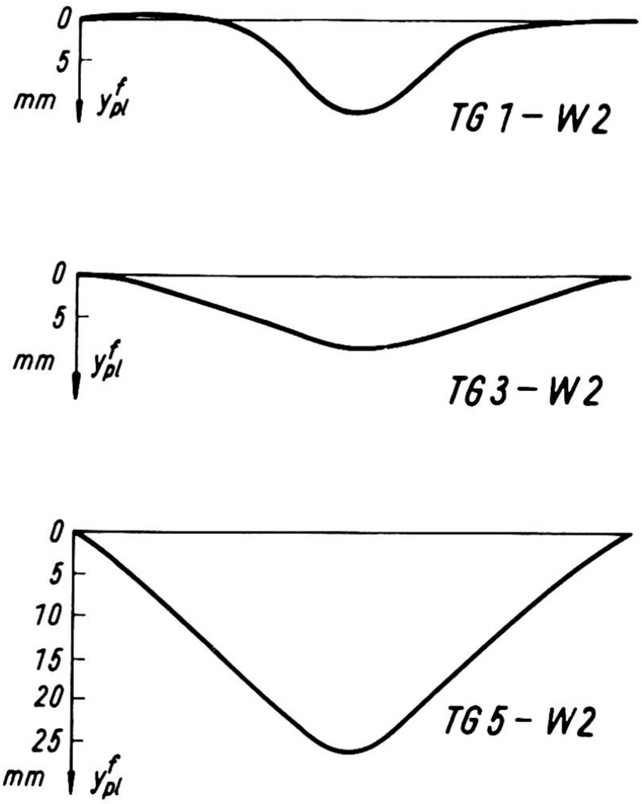
0
5
mm
y^f_{pl}
TG 1 – W2
0
5
mm
y^f_{pl}
TG 3 – W2
0
5
10
15
20
25
mm
y^f_{pl}
TG 5 – W2

Fig. 3c

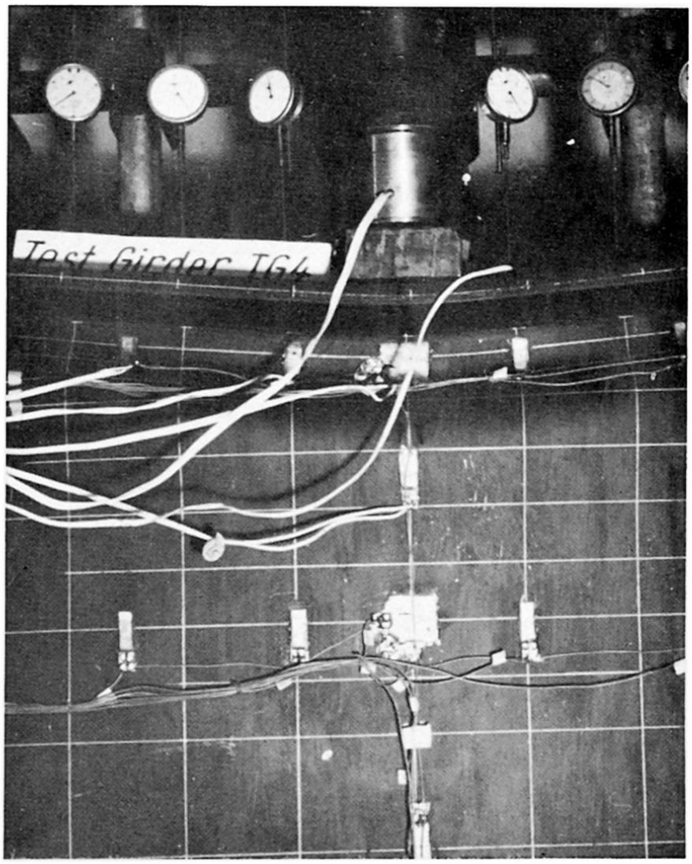
Test Girder TG4

Fig. 3d

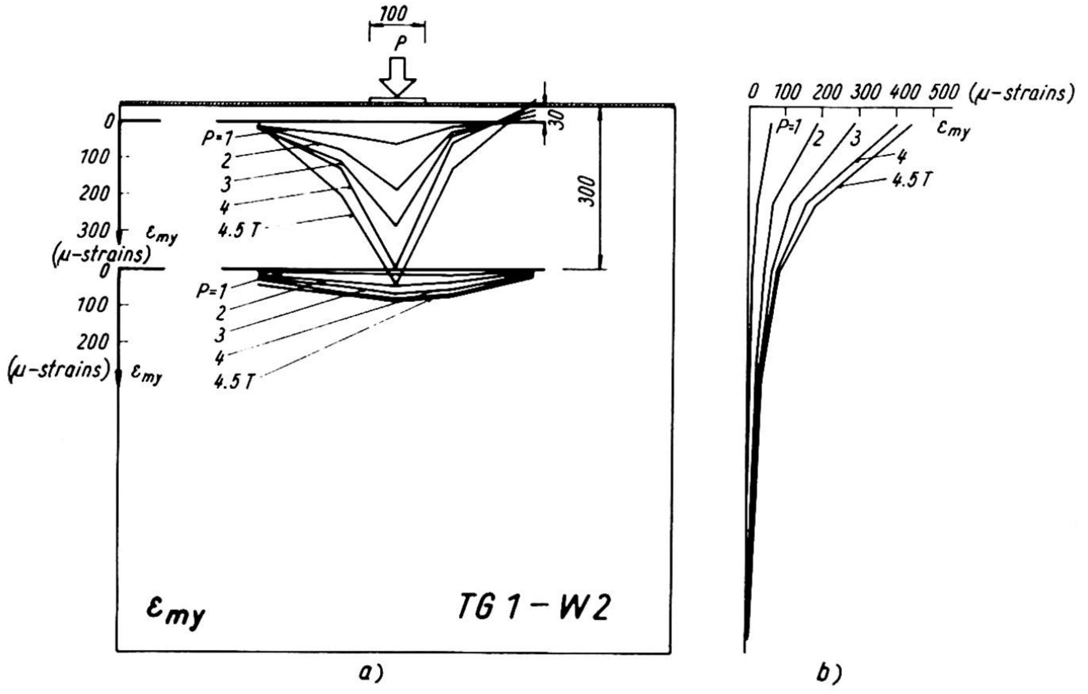

Fig. 4

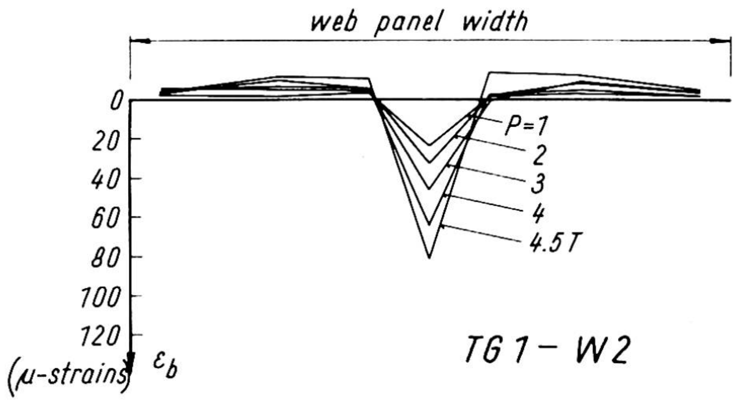

Fig. 5

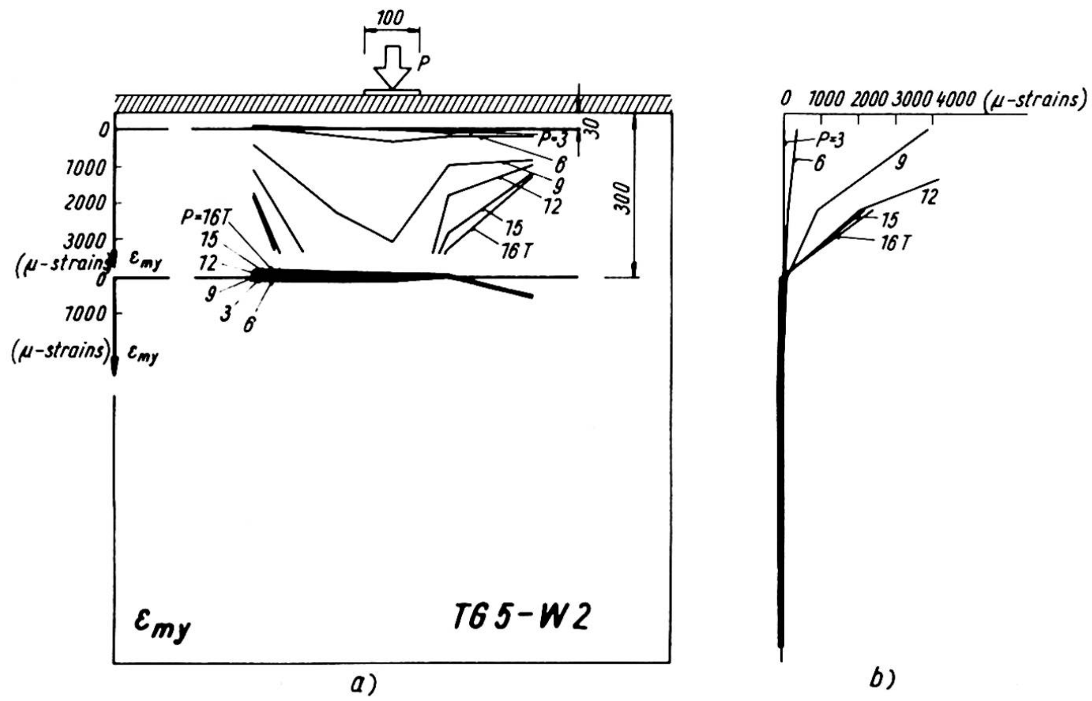

Fig. 6

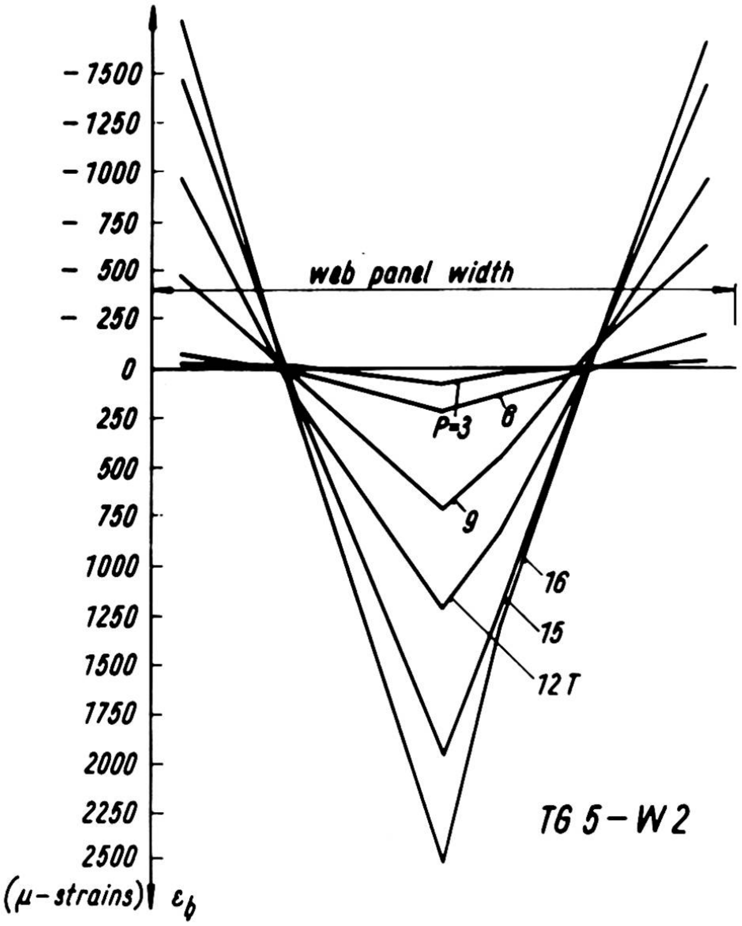

Fig. 7

flange of the same girder are plotted in Fig. 5.

The membrane strain distribution in web W 2 of girder TG 5 (heavy flanges) is shown in Fig. 6, the bending strains in the flange of the same girder are given in Fig. 7.

A comparison of the membrane strain patterns plotted in Figs. 4 and 6 again shows the considerable influence of flange inertia upon the post-buckled performance of the web. In the case of a girder with flexible flanges, the membrane stress pattern, like the buckled surface of the web discussed above, is localized in the neighbourhood of the partial edge load. Moreover, in this case are the strains still small for a load amounting to 90 % of the experimental load-carrying capacity. This indicates that the upper flange and the adjacent part of the web buckled inwardly (and the girder failed) before, or shortly after, the onset of yielding in the web. On the other hand, for a girder with rigid flanges, the stress pattern is wider (more distributed over the width of the web panel); and, even after the web has plastified in a considerable portion, the girder can sustain further load - thanks to the rigidity of the boundary framework consisting of the flanges and vertical stiffeners. Besides that, in this case the collapse of the girder is a slower process (and, therefore, not so dangerous a type of failure) than that which occurs with a girder having flexible flanges.

The ultimate loads P_{ult} of the test girders are given in Tables 1a, b, and the ratios P_{ult}/P_{cr}^{RB} (P_{cr}^{RB} denoting the critical load evoluated by Rockey's theory /5/, which takes account of flange dimensions) are plotted, in terms of the flange stiffness parameter I_f/a^3t and of the depth-to-thickness ratio $\lambda = b/t$ of the web, in Fig. 8. An analysis of the tables and figure indicates that thin webs subjected to a concentrated load, applied on to the upper flange between the vertical stiffeners of the web, manifest (like thin webs subjected to shear, bending and the like) a considerable post-critical reserve of strength, which ought to be taken into account in an optimum design of steel plate girders. This post-buckled strength grows with the depth-to-thickness ratio of the web and with the moment of inertia of the flange.

The effect of flange stiffness is very significant. For example, for girder TG 1, which had flexible flanges with

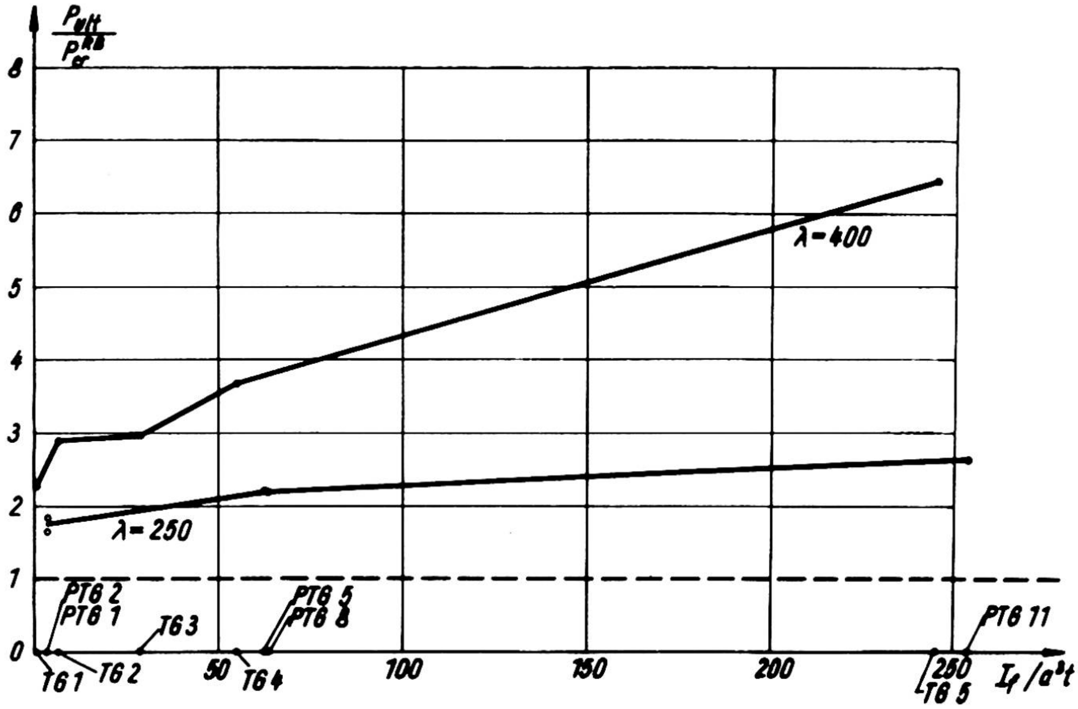

Fig. 8

I_f/a^3t = 0,89, the load-carrying capacity was 5 tons. On the other hand, for girder TG 5, having rigid flanges with I_f/a^3t = 254.4, the ultimate load attained 18 tons; which is 260% higher than the abovementioned collapse load of TG 1.

5. Cyclic Load Tests

The other part of the investigation dealt with "breathing" of the web, with stability of plastic post-critical web deflection and with incremental collapse.

The position of the concentrated load was the same as in the case of static tests; but the load cycled between 0.5 T and P_i , P_i denoting various loading steps. For each loading step, 1000 loading cycles were applied.

Three questions then needed replying:

(i) When a girder, subjected to a load cycling between 0.5T and an amplitude value P, operates in the plastic range, does an increase in web deflection occur during a certain number of loading cycles?

(ii) If it is so, do these deflection increments cease after a limited number of cycles of load applications?

(iii) Does the aforesaid deflection increase lead to a premature failure of the girder and to a reduction in its ultimate load, if compared to the value resulting from a static test?

Thanks to deflections and strains being measured carefully on an automatic recorder Ultralette, it was possible to give answers to the abovementioned questions.

An increase in web deflection (and strain) under a cyclic load was observed frequently in the plastic stage of the tests (see, for example, Fig. 9). This phenomenon "shook down", however, after a few (usually 3-5) cycles, the deflection

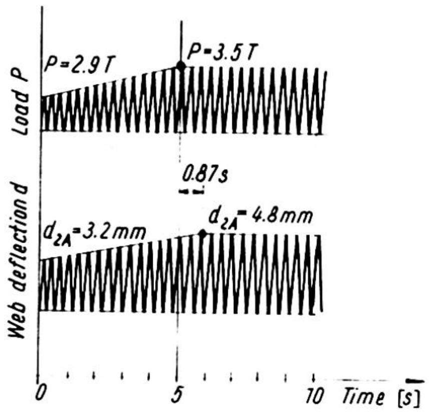

Fig. 9

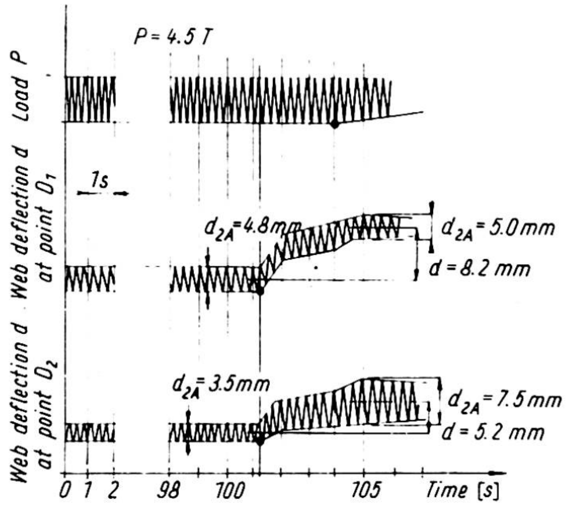

Fig. 10

stabilized, and the girder was able to sustain a higher load (Fig. 9). This happened for several successive loading steps; and only then the girder failed by deflection instability and incremental collapse (Fig. 10).

The failure loads P_{ult} resulting from the cyclic load tests are listed in Tables 1a, b and plotted, in terms of the flange stiffness I_f/a^3t and the depth-to-thickness ratio λ, in Fig.11.

In almost all tests, the cyclic ultimate loads were not lower than the load-carrying capacities resulting from the corresponding static experiments; and, in several cases, they were even higher. The cyclic loading and the incremental collapse did not, therefore, lead to any reduction in ultimate strength.

An inspection of Tables 1a, b and Fig. 11 also shows that the load-carrying capacities P_{ult} grew substantially with the flange stiffness, thereby demonstrating again the beneficial effect of flanges of great inertia.

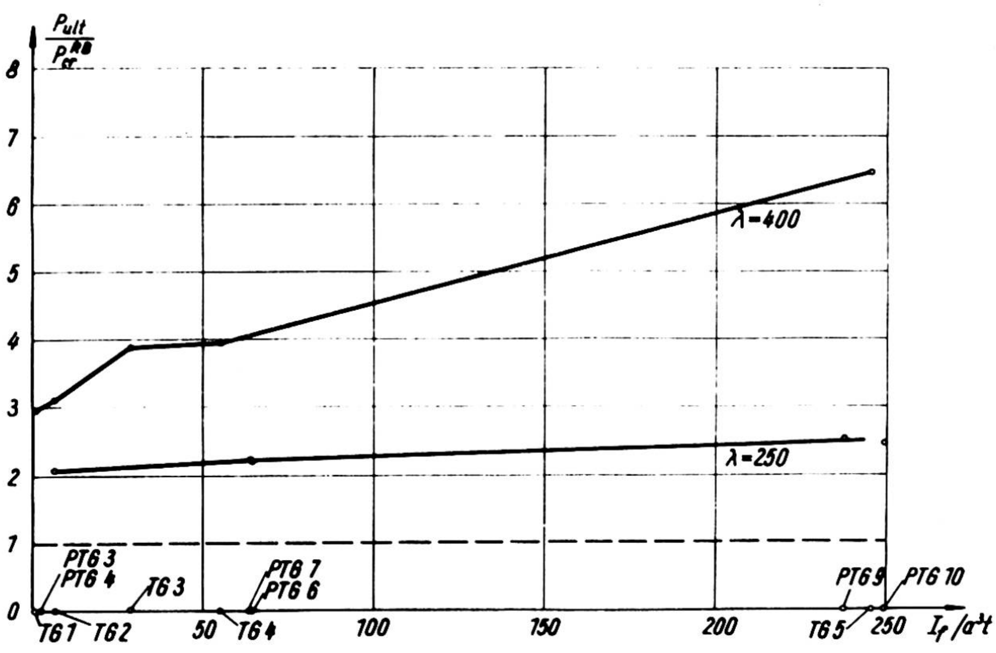

Fig. 11

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Summary

The paper deals with the ultimate load behaviour of thin webs subjected to a) static b) cyclic narrow partial edge load. An analysis of the experimental results shows that such webs (like those in shear, bending, etc.) posses a considerable post-buckled reserve of strength. It was also demonstrated that the post-critical behaviour and the ultimate load of the girder were very significantly affected by the flexural rigidity of flanges.