Zeitschrift: IABSE congress report = Rapport du congrès AIPC = IVBH Kongressbericht

Band: 8 (1968)

Artikel: Behaviour of longitudinally reinforced plate girders

Autor: Owen, D.R.J. / Rockey, K.C. / Skaloud, M.

DOI: https://doi.org/10.5169/seals-8780

DISCUSSION PRÉPARÉE / VORBEREITETE DISKUSSION / PREPARED DISCUSSION

Behaviour of Longitudinally Reinforced Plate Girders

Comportement de poutres avec raidisseurs longitudinaux

Das Verhalten des Vollwandträgers mit Längssteife

D.R.J. OWEN
M.Sc., Ph.D.
Lecturer in Civil Engineering, University of Wales, University College, Swansea

K. C. ROCKEY
M.Sc. (ENG.), Ph.D., MICE
Professor of Civil and Structural Engineering
University of Wales
University College
Cardiff

M. ŠKALOUD
Doc., CSc., Ing.
Senior Research Fellow
Czechoslovak Academy of Science
Institute of Theoretical and Applied Mechanics
Prague

1. INTRODUCTION

During the past two decades a great deal of research has been conducted on plate girders to determine the influence of the rigidity of longitudinal stiffeners upon the behaviour of plate girders. Since this work has been fully documented in earlier papers [1-3] and by Massonnet in the excellent paper he has presented at this conference, no detailed survey of published work will be given here and references will be confined to those papers of direct association with the study presented in this paper.

Massonnet [1,4-7] was one of the earliest researchers to examine the influence of stiffener rigidity upon the behaviour of plate girder webs. From his tests on double sided stiffeners, he noted that for stiffeners to behave effectively in the post buckled range it was necessary that they should have a rigidity $\gamma = k\gamma^*$, where γ^* is the theoretical rigidity which an ideal stiffener should have according to the linear theory of web buckling, in order to form a nodal line when the adjacent panels buckle. Massonnet then showed how k varied with the position of the longitudinal stiffeners and arrived at the values given below:-

Distance Between Horizontal Stiffener and Compression Flange	k
0.5d	3
0.33d	4
0.25d	6
0.20d	7

In earlier work on aluminium plate girders one of the Authors [2] observed that a value of k equal to 2 would be sufficient for single, double sided stiffeners placed at 0.2d from the compression flange.

These aluminium girders were of bolted construction, with relatively stiff flange assemblies and initially flat webs. Consequently, these girders behave differently in the immediate post buckled range ($W/W_{cr} > 1$) than a welded girder which is initially distorted and subjected to the deleterious influence of the residual stresses caused by the welding processes. Theoretical studies of the post buckled behaviour of stiffened web plates by Skaloud [8] and jointly by Massonnet, Donea and Skaloud [9-11] are in general agreement with the experimental observations referred to above.

Since 1961, a comprehensive study of many of the problems encountered with welded steel girders has been in hand at the University of Lehigh. Cooper [12,13], reporting on pure bending tests conducted on girders reinforced by a single longitudinal stiffener, commented that "the longitudinal stiffeners which were used in these tests had no significant effect upon the observed ultimate loads, except for specimen LB6 where a 11% increase in ultimate load was realised". However, the test data given by Cooper indicates that failure occurred at less than twice the theoretical buckling load calculated on the assumption that the web was simply supported along its boundary. Thus in this case one would not expect the influence of stiffener rigidity upon the post buckled behaviour of the web plate to be too significant.

In a more recent report, which has just become available to the writers, Cooper [14] presents a most extensive report on further tests conducted on girders having web plates reinforced by a single longitudinal stiffener; in this report he concludes that "if properly proportioned longitudinal stiffeners are provided, a significant increase in bending strength can result". As will be seen later, this conclusion is in general agreement with one of the findings of the present Authors.

The present study was conducted to examine in particular the following:-

1. The behaviour of single sided longitudinal stiffeners on webs subjected to pure bending stresses. The study dealing with web plates reinforced by either one or two longitudinal stiffeners.

2. The influence of the ratio of γ/γ^* upon the collapse load of the girders.

II. DESIGN OF GIRDERS

The design details of the girders tested are given in Figure 1 and Table 1.

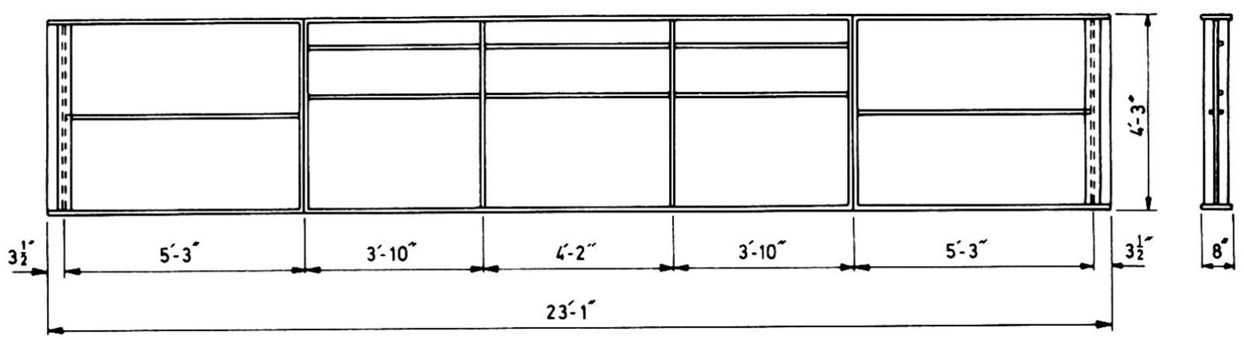


FIGURE 1 - DETAILS OF TEST GIRDERS

Since the object of the investigation was to determine the behaviour of girders subjected to pure bending, only that portion of the girders loaded accordingly was of interest. Therefore, it was decided to use girders of the design shown in Figure 1, with the detachable end panels which could be repeatedly used. These end panels which were designed to ensure that failure always took place in the central panels, were attached to the central section by means of ¾ in. diameter, high tensile steel bolts distributed across the depth of the girder. In addition, it was found necessary to employ a short cover plate welded to the tension flange of the central section and bolted to the end panels, since during the testing of girder TG7-1 (the first test conducted) a weld fractured in this region, the tension flange breaking away from the vertical member.

TABLE NO. 1

TEST GIRDERS	NO. OF LONGI-TUDINAL STIF-FENERS	POSITION OF STIFFENERS		ACTUAL DIMENSION OF STIFFENERS (IN.)		γ/γ^*	ULTIMATE LOAD TONS
		FIRST (TOP)	SECOND (BOTTOM)	FIRST (TOP)	SECOND (BOTTOM)		
TGO	0	-	-	-	-	-	48.2
TG1-1	1	0.2d	-	0.713x0.187	-	0.89	55.5
TG2-1	1	0.2d	-	0.872x0.187	-	1.63	57.15
TG4-1	1	0.2d	-	1.323x0.187	-	5.8	59.75
TG7-1*	1	0.2d	-	0.87 x0.187	-	3.28	44
TG1-2	2	0.123d	0.40d	0.765x0.187	0.758x0.187	0.64	54.75
TG2-2	2	0.123d	0.40d	1.008x0.187	1.014x0.187	1.51	52.5
TG3-2	2	0.123d	0.40d	1.262x0.187	1.261x0.187	2.94	62.5
TG4-2	2	0.123d	0.40d	1.503x0.187	1.531x0.187	5.11	64.0
TG5-2	2	0.123d	0.40d	1.741x0.187	1.746x0.187	7.75	64.75

* Double Sided Stiffener.

The central panel of one test girder, TG-O, was only reinforced by transverse stiffeners, this test thus providing a datum against which to judge the efficiency of the longitudinal stiffeners which were used on the other test panels. Four girders were fitted with a single longitudinal stiffener placed at one fifth of the clear web depth from the compression flange which is the optimum position when the flanges provide a simple support [15,16]. Three of these girders were fitted with single sided stiffeners, the fourth with a double sided stiffener.

The third test series consisted of five girders with two in number single sided longitudinal stiffeners whose dimensions are also given in Table 1. The stiffeners were again positioned such as to give the optimum buckling load for the girders [17].

The girders were of welded construction. On the recommendation of the British Welding Research Association, a staggered welding technique was used to weld the stiffeners to the web plate in an attempt to minimise initial deformations of the stiffeners and web plate. Unfortunately, even with this procedure, quite large initial deformations were formed, see Table 2.

The ratio of panel depth to web thickness was chosen to be 750:1, the web plate being 0.066 in. thick and having a clear web depth between flanges of 50 in. This ensured that the ultimate load as calculated from simple plastic theory was approximately three times the critical load for girders with two lines of longitudinal stiffeners and six times the critical load for girders reinforced by a single longitudinal stiffener.

TABLE NO. 2

Maximum Initial Deformations (ins.)

	FIRST STIFFENER	SECOND STIFFENER	TOP PANEL	MIDDLE PANEL	LOWER PANEL
TGO	-	-	0.3	-	-
TG1-1	0.192	-	-0.241	-0.281	-
TG2-1	0.152	-	0.158	-0.193	-
TG4-1	0.056	-	0.166	-0.338	-
TG1-2	-0.032	0.37	-0.078	-0.113	-0.092
TG2-2	-0.110	0.138	-0.11	0.133	0.183
TG3-2	0.092	-0.05	-0.091	0.138	-0.073
TG4-2	0.020	0.06	-0.087	-0.155	-0.320
TG5-2	0.040	0.117	-0.089	+0.204	0.268

The dimensions of all stiffeners and those of the flanges were so chosen as to ensure that the failure of the girder should not be influenced by any local elastic buckling of the individual elements.

III. EXPERIMENTAL APPARATUS

The essential features of the testing rig can be seen in Figure 2. The girders were simply supported at their ends on case-hardened steel rollers and loaded equally at the junction of end panel and the central section by means of two hydraulically operated jacks of 100 tons capacity. The applied load was recorded by two load cells connected to the Elliott load indicators which can be seen in the right-hand side of Figure 2.

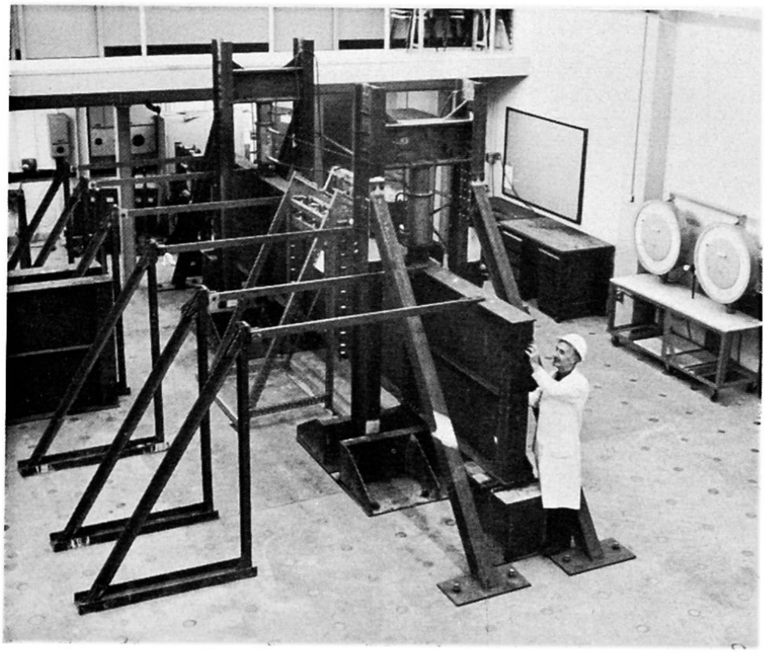


FIGURE 2
GENERAL VIEW OF A GIRDER UNDER TEST

The compression flange was restrained laterally by the use of the six stabilising trusses which are shown in Figure 2. Lever arms were pin connected at one end to these rigid trusses and at the other end to the compression flange of the girder. These lever arms, which were 6ft. long, allowed free vertical movement of the girder but restricted the lateral movement of the compression flange.

The rotation, vertical and lateral movements of the central panel of the test section, were recorded by means of the dial gauge system shown in Figure 3. The frame supporting the dial gauges was firmly bolted to the floor.

It was essential that the deflection of the longitudinal stiffeners was measured with extreme accuracy, and this was achieved by means of the dial gauge system shown in Figure 4. This apparatus was clamped to the transverse stiffeners by specially designed clamps, which ensured that the bar carrying the gauges remained unstressed during the loading of the girder. Eleven dial gauges were distributed along each stiffener. For the testing of the girder with no longitudinal stiffeners, TG-O, the same device, attached to the flanges, was used to check that the transverse stiffeners remained effectively rigid.

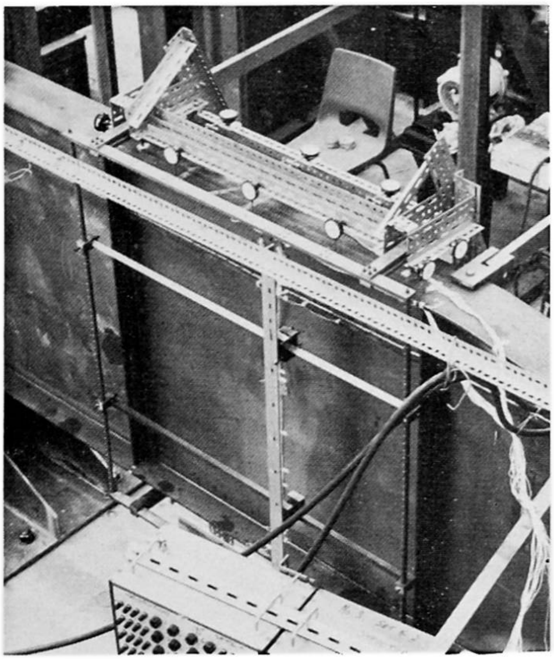


FIGURE 3

In order to be able to determine the effectiveness of the various stiffeners in restricting the lateral deformation of the web plate under load, the device shown in Figures 3 and 5 was used to measure web plate deflections over the whole of the centre panel. This framework was spring-loaded on to the compression and tension flanges in the plane of the web plate, small centering holes being used to accurately position the frame. Thus the apparatus was completely unaffected by any rotation induced in the flanges. Deflections were determined relative to the vertical aluminium bar which contained slots at convenient vertical intervals. This bar could freely slide along a pair of horizontal guides, thus allowing readings to be taken at any vertical section. Trial tests carried out with this apparatus established that very good reproducibility of results was obtained.

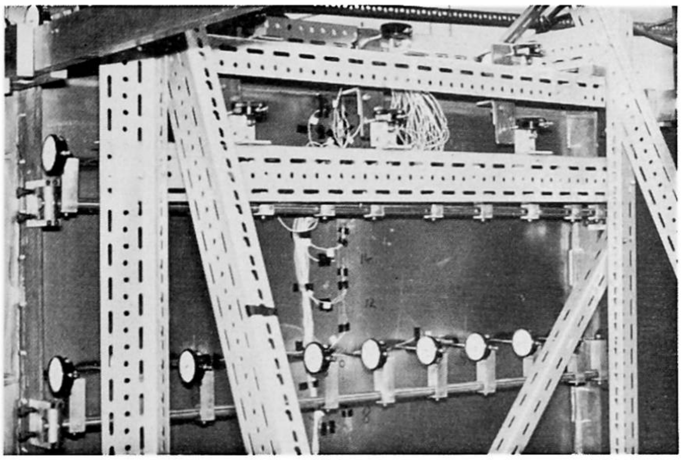


FIGURE 4
APPARATUS USED TO RECORD LATERAL DEFLECTIONS OF STIFFENERS

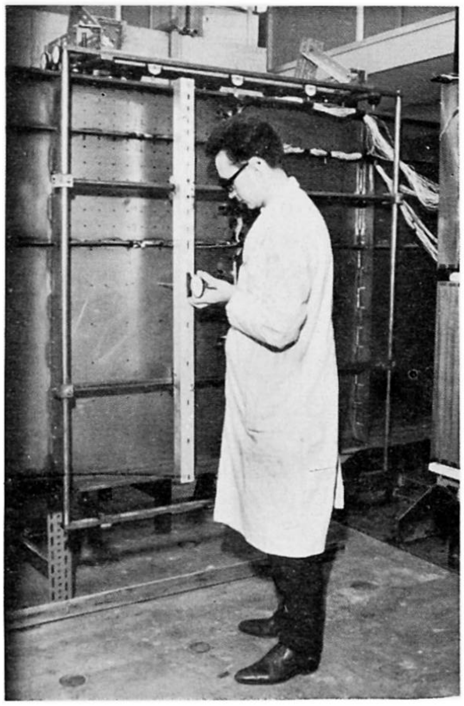


FIGURE 5
APPARATUS USED TO RECORD DEFLECTIONS OF WEB PLATE

Each girder was instrumented with electrical resistance strain gauges, ranging from over a hundred gauges for certain girders with two lines of longitudinal stiffeners to only twenty-five for girder TG-O. In each case gauges were attached to the longitudinal stiffeners as well as the web plate and flanges. Wherever possible orthogonal pairs of gauges were used to enable the evaluation of stress. Material tests were carried out on the web and flange material used in each girder and the synopsis of the results obtained is given in Table 3.

IV. PROCEDURE FOR TESTS

The strain gauge bridges were initially balanced to give zero readings and the initial readings of the various dial gauges were recorded. The lateral deflection of the web plate in the central panel was measured at a sufficient number of points to enable a contour plot of the initial deformed shape to be drawn. For the large panel adjacent to the tension flange, readings were taken over a 5 in. square mesh. For the panel adjacent to the compression flange in the case of those girders with one line of stiffeners and the panel bounded by the stiffeners in the case of the girders with two stiffeners, readings were taken on a 2 in. square grid. For the case of girders with two longitudinal stiffeners, readings in the panel adjacent to the compression flange were taken at 1½ in. intervals in the vertical direction and at 2 in. intervals in the longitudinal direction.

Load was applied to the girder in increments of 2½ tons, the strain gauge readings being noted at these intervals. In addition, in the initial stages, at each 10 ton load increment the stiffener and flange deflections were noted. However, as the ultimate load was approached, these readings were recorded more frequently.

Lateral deflection readings to provide contour plots of the entire centre panel were also taken at zero load and at load values beyond the theoretical buckling load.

V. RESULTS

Typical failures are shown in Figure 6. The failure mechanism for the unstiffened girder TG-0 can be seen in Figure 6, whilst Figure 7 shows girder TG2-1 after failure and Figure 8 shows girder TG5-2 after collapse.

Bar the sole exception of girder TG7-1 where collapse of girder was due to a weld fracture in the tension zone, all remaining girders failed by the inward buckling of the compression flange. This inward collapse of the compression flange occurred suddenly with very little lateral movement or twisting. Figure 9 shows girder TG4-2 after collapse and indicates that the compression flange was on the point of collapse along its complete length.

TABLE NO. 3

MATERIAL	LIMIT OF PROPORTIONALITY TONS/IN^2	LOWER YIELD STRESS TONS/IN^2	UPPER YIELD STRESS TONS/IN^2	ULTIMATE STRESS TONS/IN^2
WEB PLATE	8.68	13.66	13.98	21.31
FLANGE PLATE	12.36	15.66	15.98	27.37

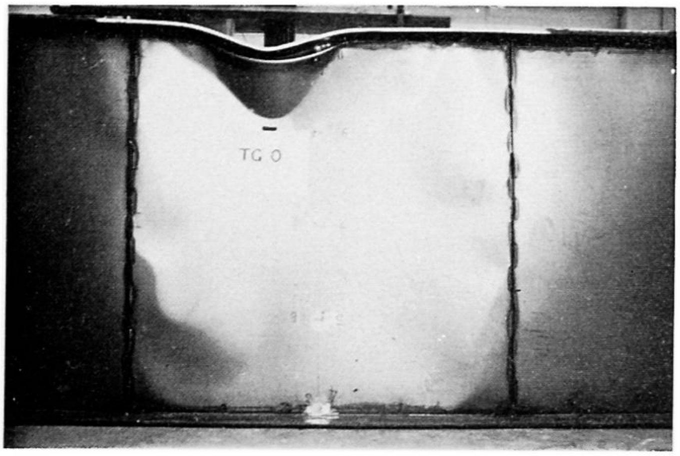


FIGURE 6

FIGURE 7

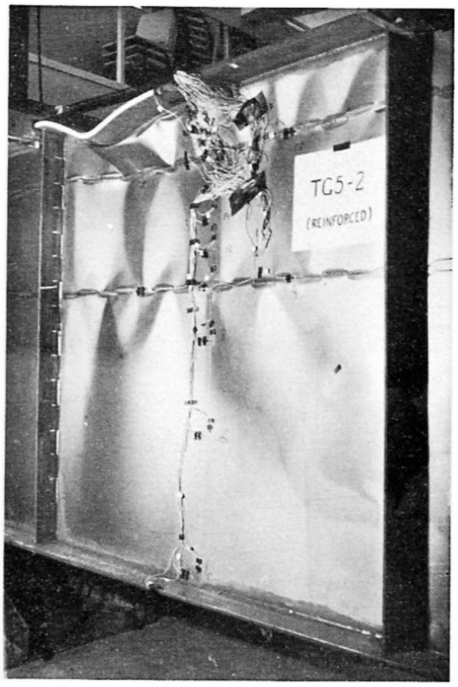


FIGURE 8

The collapse loads for the girders tested are given in Table 1, together with the ratio of the flexural rigidity of the longitudinal stiffeners to the theoretical optimum value for each girder. Figure 10 shows the percentage gain in load carrying capacity obtained by the use of stiffener systems with increasing flexural rigidity. The benefits of employing fully effective longitudinal stiffeners are clearly demonstrated. Also shown is the theoretical ultimate load for the girders as calculated from the simple plastic theory, ignoring the effects of strain hardening.

The growth of the maximum lateral deflection of the longitudinal stiffeners with increasing applied load is shown for the case of a single longitudinal stiffener in Figure 11 and corresponding diagrams for the case of two lines of longitudinal stiffeners in Figures 12 and 13. For the girders with two lines of longitudinal stiffeners it will be noted that the deflection of the top stiffener, i.e., the one nearer the compression flange significantly exceeds that of the lower stiffener. It will also be noted that there is a tendency for the stiffener deflection to decrease with increasing value in the ratio γ/γ^*.

FIGURE 9
VIEW OF COMPRESSION FLANGE AFTER COLLAPSE

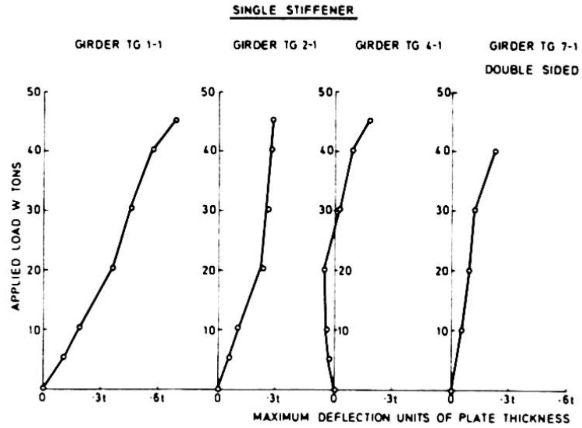


FIGURE 11
APPLIED LOAD, MAXIMUM LATERAL DEFLECTION PLOTS. SINGLE LONGITUDINAL STIFFENER

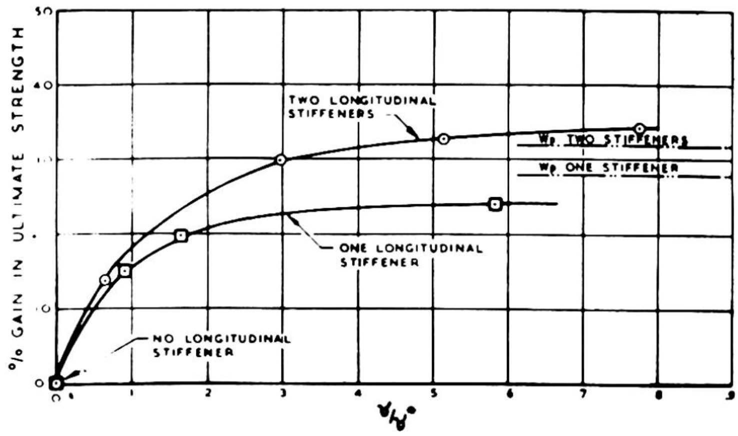


FIGURE 10

The web plate deflection readings enabled contour maps of the deformed surface to be drawn, a computer programme being used to determine the contour plots. For those girders reinforced by a single longitudinal stiffener, in each case the panel adjacent to the compression flange tended to produce the classical sine wave patterns usually associated with bending tests. These can be seen in Figure 14, which gives the additional web deflections recorded in Girder TG2-1. However, due to the increased buckling resistance, for those girders with two lines of stiffeners the upper two panels did not develop as well defined buckling patterns.

It also follows from the analyses of the deflected web plates that stiffeners having a flexural rigidity close to the theoretical optimum value tend to deflect with the web plates and do not form a nodal line in the post buckled range.

From the contour plots of the initial web deformation, the maximum positive and negative panel deflections could be found and these are given in Table 2, together with the corresponding values for the longitudinal stiffeners.

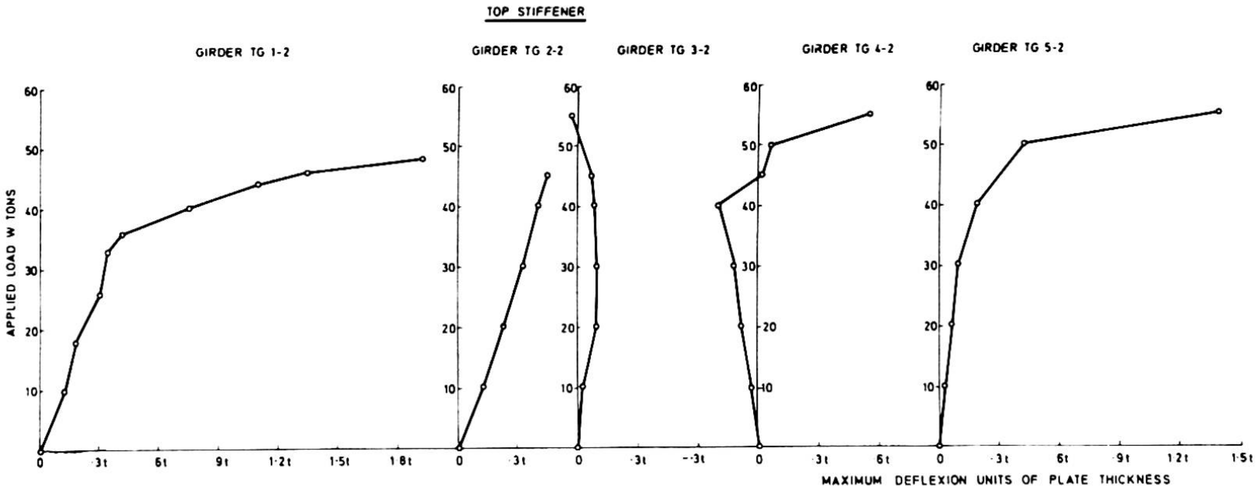


FIGURE 12
APPLIED LOAD/MAXIMUM DEFLECTION PLOTS FOR TOP STIFFENER AT 0.123d FROM COMPRESSION FLANGE. WEB REINFORCED BY TWO STIFFENERS

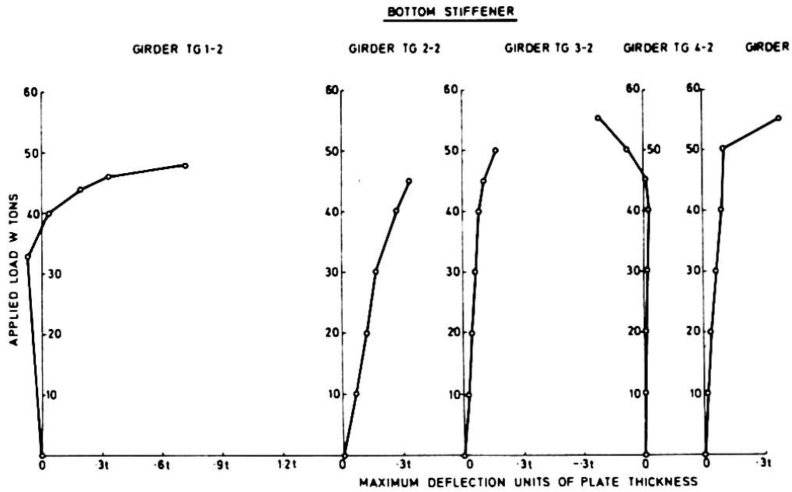
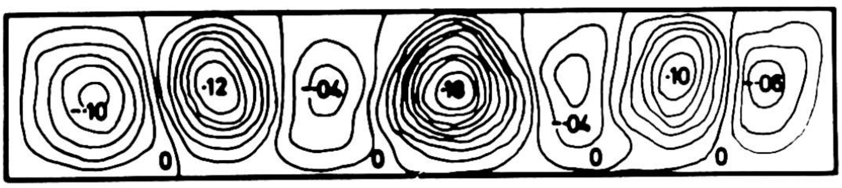


FIGURE 13
APPLIED LOAD/MAXIMUM DEFLECTION PLOTS FOR BOTTOM (SECOND) STIFFENER AT 0.4d FROM COMPRESSION FLANGE WEB REINFORCED BY TWO STIFFENERS

In Figure 15 the strain variation along the centre line of the girder TG5-2 is shown. The strains on both web plate faces are given for various load increments, together with the mean longitudinal strain values. This clearly demonstrates the increasing ineffectiveness of portions of the web plate in the compression zone in resisting stresses as the loading is increased.

The mid-plate longitudinal strains on the centre line section of the girder are shown for various load values in Figure 16. The shift in the position of the neutral axis towards the tension flange brought about by the ineffectiveness of parts of the web in the two upper panels, is well demonstrated.



TG 2-1 $W = 45^T$

FIGURE 14
ADDITIONAL DEFLECTION PATTERN DEVELOPED IN PANEL ADJACENT TO COMPRESSION FLANGE. ONE LONGITUDINAL STIFFENER

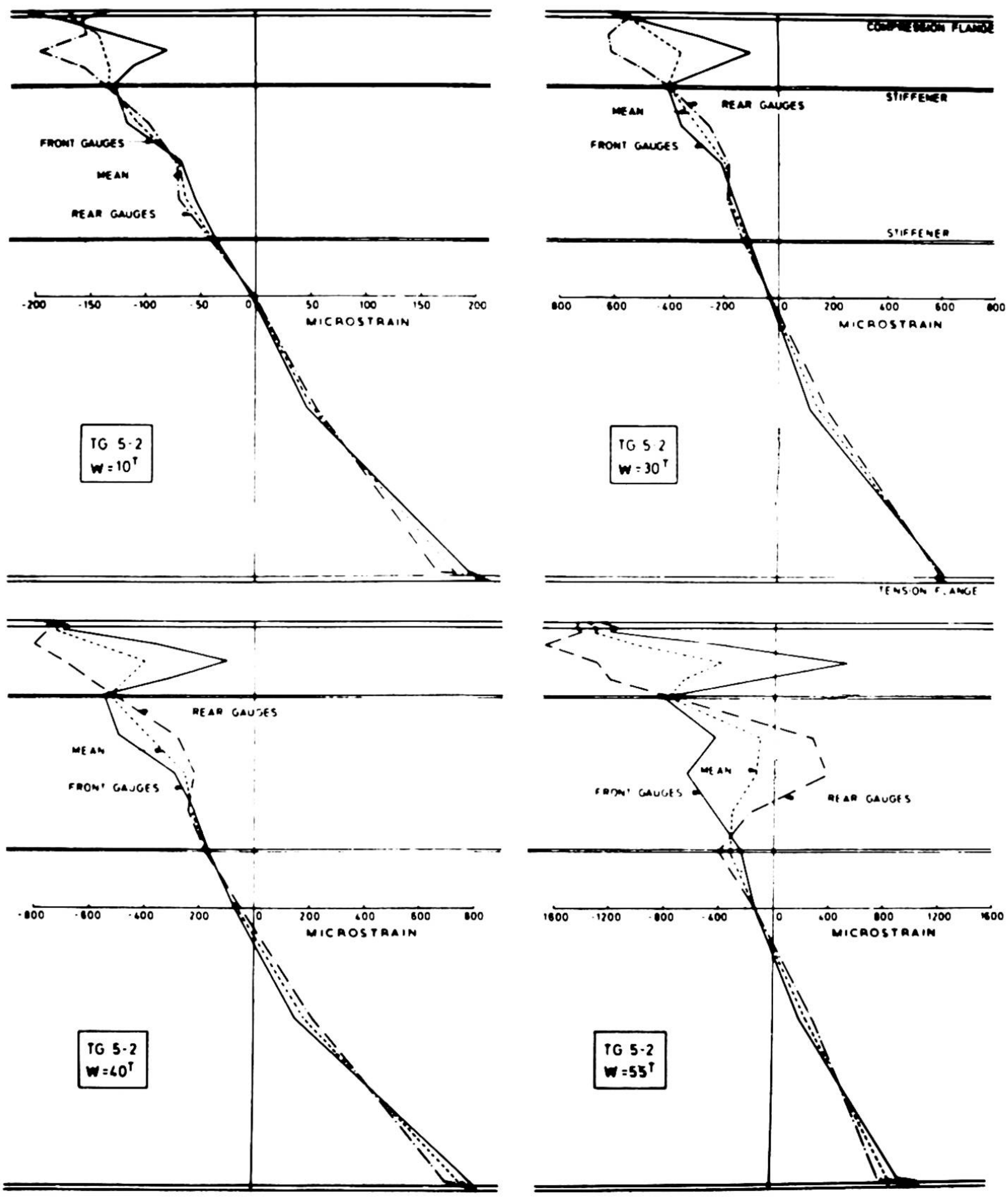


FIGURE 15
SURFACE AND MEAN STRAIN ACROSS DEPTH OF
GIRDER TG5-2 AT MIDSPAN

The effective section of a longitudinally stiffened web plate when loaded in the post buckled range is diagramatically illustrated in Figure 17. The loss of effective width results, as shown above, in the lowering of the neutral axis, a reduction in the effective sectional modulus and a corresponding increase in the compression strains. The loss of effective width is a function of the load ratio W/Wcr [18]. Thus the lower the buckling load, the greater the loss in effective width of those panels loaded in compression. It is for this reason that the girders reinforced by a single longitudinal stiffener have lower ultimate loads than those girders reinforced by a double line of stiffeners.

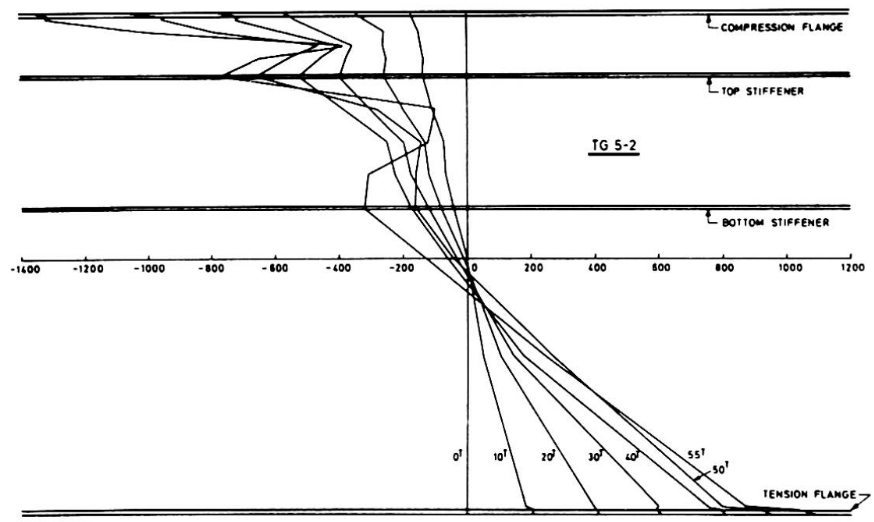


FIGURE 16
MEAN STRAINS ACROSS DEPTH OF GIRDER
TG5-2 SHOWING SHIFT OF NEUTRAL AXIS

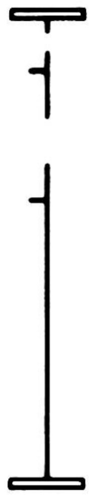


FIGURE 17
REDUCED EFFECTIVE SECTION
DUE TO BUCKLING

Thus it will be seen that by providing suitable longitudinal reinforcement in the compression zone it will be possible to design girders so that they develop ultimate loads very close to the plastic collapse load, given by simple plastic theory ignoring the effect of web buckling. A design procedure based on these studies will be presented in a forthcoming article [19].

VI. CONCLUSION

The present study has shown that (a) longitudinal stiffeners considerably influence the buckled pattern of the web, the stress distribution and the ultimate load of the girders, the beneficial influence of the longitudinal stiffeners being a function of their relative flexural rigidity, and (b) by reinforcing a web plate by suitably proportioned longitudinal stiffeners it is possible to achieve the full plastic collapse strength of a plate girder.

VII. ACKNOWLEDGEMENT

The Authors wish to acknowledge with grateful thanks the support received from the British Constructional Steelwork Association and the Civil Engineering Information and Research Association for their financial support.

Thanks are also due to the British Welding Research Association for their assistance in fabricating the girders.

Thanks are also due to Mr. R. Jones and Mr. H. John of the Technical Staff at the University College, Swansea for their very considerable help both during the tests and in the preparation work.

VIII. SYMBOLS

t	thickness of web plate
d	clear depth of web plate
E	Young's Modulus
μ	Poisson's Ratio
$D = Et^3/12(1-\mu^2)$	flexural stiffeners of unit width of plate
EI	flexural rigidity of a longitudinal stiffener
$\gamma = \frac{EI}{Dd}$	
W	applied load
W_{cr}	theoretical load to cause buckling of an ideally stiffened plate without initial deformations
W_p	plastic collapse load
	all other symbols are defined as they appear in the text

IX. BIBLIOGRAPHY

1. Ch. Massonnet. Stability considerations in the design of plate girders. Proc. A.S.C.E., Journal Structural Div., Vol. 86, pp. 71-97, January 1960.

2. K. C. Rockey. Aluminium plate girders. Paper presented at the symposium. Aluminium in structural engineering, held by the Institution of Structural Engineers, June 1963, published in Proceedings of Symposium, June 1964, pp. 80-98.

3. P. B. Cooper. Literature survey on longitudinally stiffened plates. Fritz Engineering Lab. Report No. 304.2, September, 1963.

4. Ch. Massonnet. Recherches expérimentales sur le voilement de l'âme des poutres à l'âme plaine. Bull. Centre Etudes Liège, Vol. 5, pp. 67-240, 1951, et publ. Préliminaire 4e Congrès A.I.P.C., Cambridge-London, pp. 539-555, 1952.

5. Ch. Massonnet. Essais de voilement sur poutres a âme raidie. Mem. A.I.P.C., Vol. 14, pp. 125-186, 1954.

6. Ch. Massonnet, G. Mazy et A. Tanghe. Théorie générale du voilement des plaques rectangulaires orthotropes, encastrées ou appuyées sur leur contour, munies de raidisseurs paralleles aux bords à grandes rigidités flexionnelle et torsionnelle. Mem. A.I.P.C., Vol. 20, pp. 223-262, 1960.

7. Ch. Massonnet, G. Mazy et H. Maus. Essais de voilement sur deux putres à membrures et raidisseurs tubulaires. Mem. A.I.P.C., Vol. 32, pp. 183-228, 1962.

8. M. Škaloud. Comportement post-critique des âmes comprimées uniformément et renforcées par des raidisseurs longitudinaux. Acier-Stahl-Steel, 4, 1964.

9. M. Skaloud. Effet d'une courbure initiale sur le comportement post-critique d'une âme comprimée uniformément et reinforcée par un raidisseur longitudinal. Acier-Stahl-Steel, 5, 1965.

10. M. Škaloud, J. Donea, Ch. Massonnet. Comportement post-critique d'une plaque carée raidie cisaillée uniformément. Première portie. Solution générale et déformée de la plaque. Mem. A.I.P.C., pp. 187-210, 1967.

11. M. Škaloud, J. Donea, Ch. Massonnet. Comportement post-critique d'une plaque carée raidie cisaillee uniformement, Deuxième Partie, Répartition des contraintes et analyse de l'état limite, to be published in Mem. A.I.P.C., 1968,/1969.

12. M. A. D'Apice, D. J. Fulldery and P. B. Cooper. Static tests on longitudinally stiffened plate girders. Welding Research Council, Bulletin No. 117, October 1966.

13. M. A. D'Apice and P. B. Cooper. Static bending tests on longitudinally stiffened plate girders. Fritz Engineering Lab. Report No. 304.5, Lehigh University, 62 p., April 1965.

14. P. B. Cooper. Bending and shear strength of longitudinally stiffened plate girders. Fritz Engineering Lab. Report No. 304.6, Lehigh University, 140 p., September 1965.

15. Ch. Massonnet. La stabilité de l'âme des poutres munies de raidisseurs horizontaux et sollicitées par flexion pure. Mem. A.I.P.C., Vol. 6, pp. 234-246, 1940.

16. K. C. Rockey and D. M. A. Leggett. The buckling of a plate girder web under pure bending when reinforced by a single longitudinal stiffener. Proc. Inst. Civ. Engrs. Vol. 21, pp. 161-188, January 1962.

17. K. C. Rockey and I. T. Cook. Optimum reinforcement by two longitudinal stiffeners of a plate subjected to pure bending. Inst. J. Solids and Structures, 1965, Vol. 1, pp. 79-92. Pergamon Press Ltd.

18. Column Research Council. Guide to design criteria for metal compression members. Engineering Foundation 1960.

19. K. C. Rockey and D. R. J. Owen. An ultimate method of design for plate girders. Unpublished report.

SUMMARY

The paper presents the results of ultimate load tests carried out on 10 plate girders having an overall depth of 51 in. The test section of the girders was subjected to pure bending stresses and the web was reinforced by either one or two longitudinal stiffeners. The influence of stiffener rigidity upon both the pre and post buckled behaviour of the stiffened web was examined and the results obtained have provided relationships between the collapse load of the girder and the flexural rigidity of the longitudinal stiffeners.

RÉSUMÉ

Le présent article fait état des résultats de tests de charge maximum portant sur dix poutres à âme pleine, de 127.5 cm. (51 in.) d'épaisseur hors tout. La section des poutres sur lesquelles ont porté les tests a été soumise à des tensions visant uniquement à les courber, l'âme de chaque poutre étant renforcée par une ou par deux pièces de renfort longitudinales. L'effet de la rigidité additionnelle due aux pièces de renfort sur le comportement de l'âme des poutres, avant et après la flexion, a fait l'object d'une étude, et les résultats obtenus ont permis de préciser les rapports entre la charge provoquant la rupture des poutres et le degré de flexibilité des supports longitudinaux.

ZUSAMMENFASSUNG

Dieser Beitrag zeigt die Ergebnisse der Traglastversuche an 10 Vollwandträgern mit 127.5 cm Höhe. Der Messquerschnitt war reiner Biegung unterworfen und der Steg entweder durch eine oder zwei Längssteifen verstärkt. Der Einfluss der Stegsteifen wurde untersucht und die erhaltenen Ergebnisse haben eine Beziehung zwischen Traglast des Vollwandträgers und der Biegesteifigkeit der Längssteifen gezeigt.