Flexural and torsional failure modes of continuous thin walled beams

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Objekttyp: **Article**

Zeitschrift: **IABSE reports of the working commissions = Rapports des commissions de travail AIPC = IVBH Berichte der Arbeitskommissionen**

Band (Jahr): **4 (1969)**

PDF erstellt am: **08.08.2024**

Persistenter Link: https://doi.org/10.5169/seals-5940

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Flexural and Torsional Failure Modes of Continuous Thin Walled Beams

Les différents cas de ruine des poutres continues à parois minces soumises
à la flexion et à la torsion

Biege- und Drillbrucharten durchlaufender dünnwandiger Stäbe

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Introduction

The work described in this contribution has been undertaken as a follow up to an investigation into the stress systems obtaining in continuous thin walled structural systems subjected to combined bending and torsion. Although the project is in its early stages it was felt that the results already noted gave some indication of the complexity of the problem and if published, might encourage further research in other centres.

It is well known that cold formed thin walled sections are, by reason of their cross-sectional form, subjected to both bending and torsion in any practical application. This kind of loading produces localised high stress values which if used for an elastic design procedure can give rise to rather conservative section sizes. One approach to overcoming this difficulty is by bracing the member in such a way as to reduce the longitudinal torsional stresses. (1) Such techniques will of course lead to higher construction costs. It is possible that given a better understanding of the localised high stresses and the resulting flange buckling, a design procedure analogous to the collapse approach used in plastic design of conventional hot rolled sections, could be developed. In this way more economic use could be made of thin walled sections and their field of application increased.

It is immediately obvious that the concept of the 'plastic hinge' used in the collapse method of analysis cannot apply directly to thin walled sections. However, as will be seen from the tests described later, the overall mechanism of collapse of a thin walled continuous beam is of the same form as that occurring when a conventional hot rolled section is used. In the case of a thin walled element the plastic hinge would appear to be replaced by gross cross-sectional deformation arising from local flange buckling combined with the initiation of some plastic flaw in the material.

At the present time the emphasis of the research programme is on the experimental work and this is reflected by the contents of this contribution. Theoretical analysis is of course being developed and a brief indication of this part of the programme is also included in the closing summary.

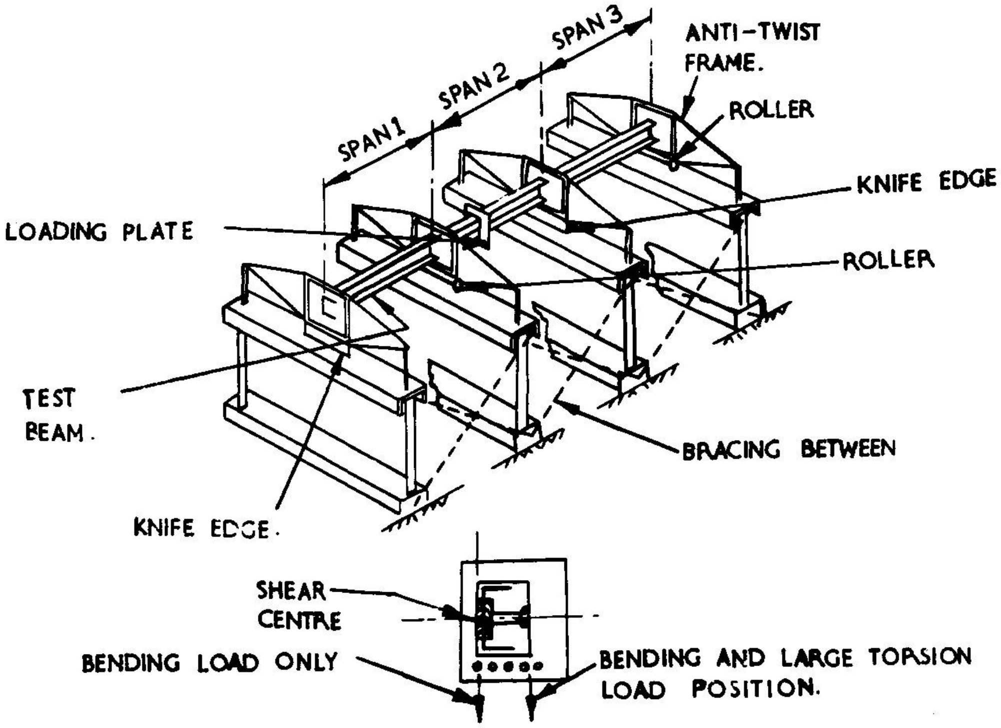

FIG. 1. DETAILS OF CONTINUOUS BEAM TEST RIG.

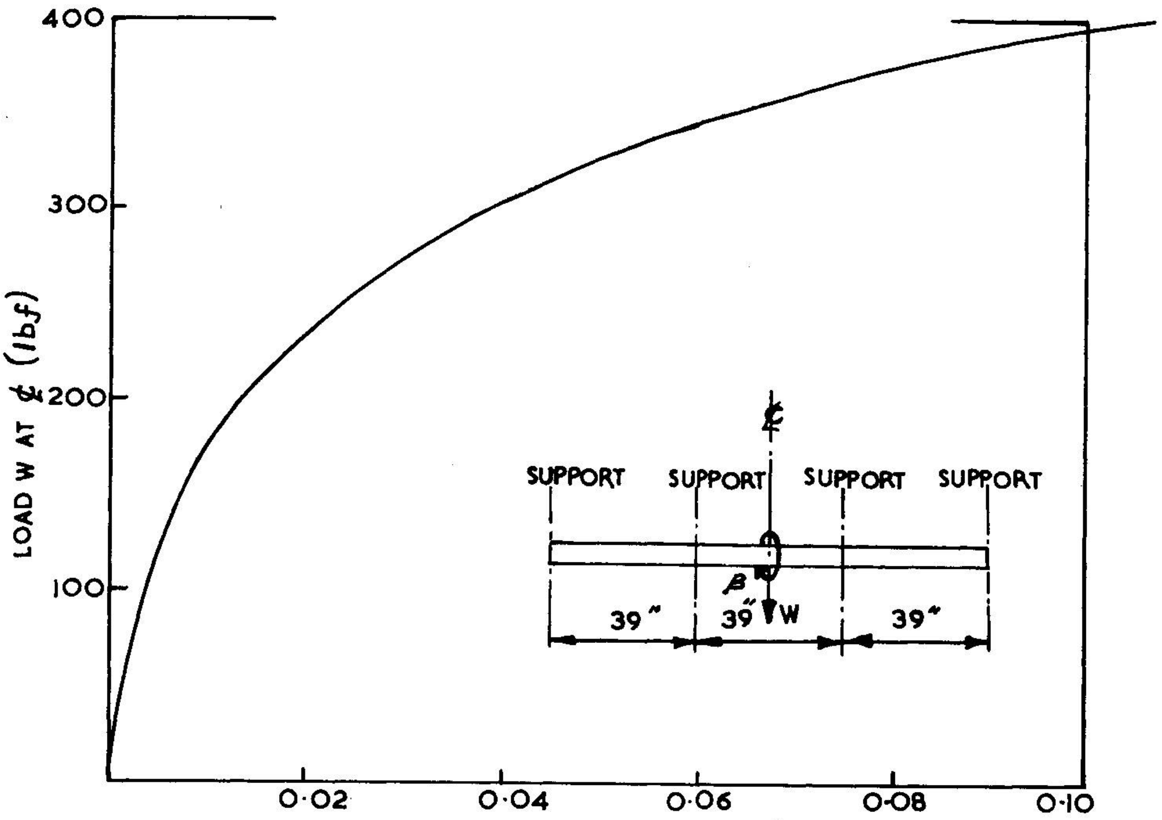

FIG. 2(a) ANGLE OF TWIST β AT ℄ (RADIANS)
FIG. 2 (a)

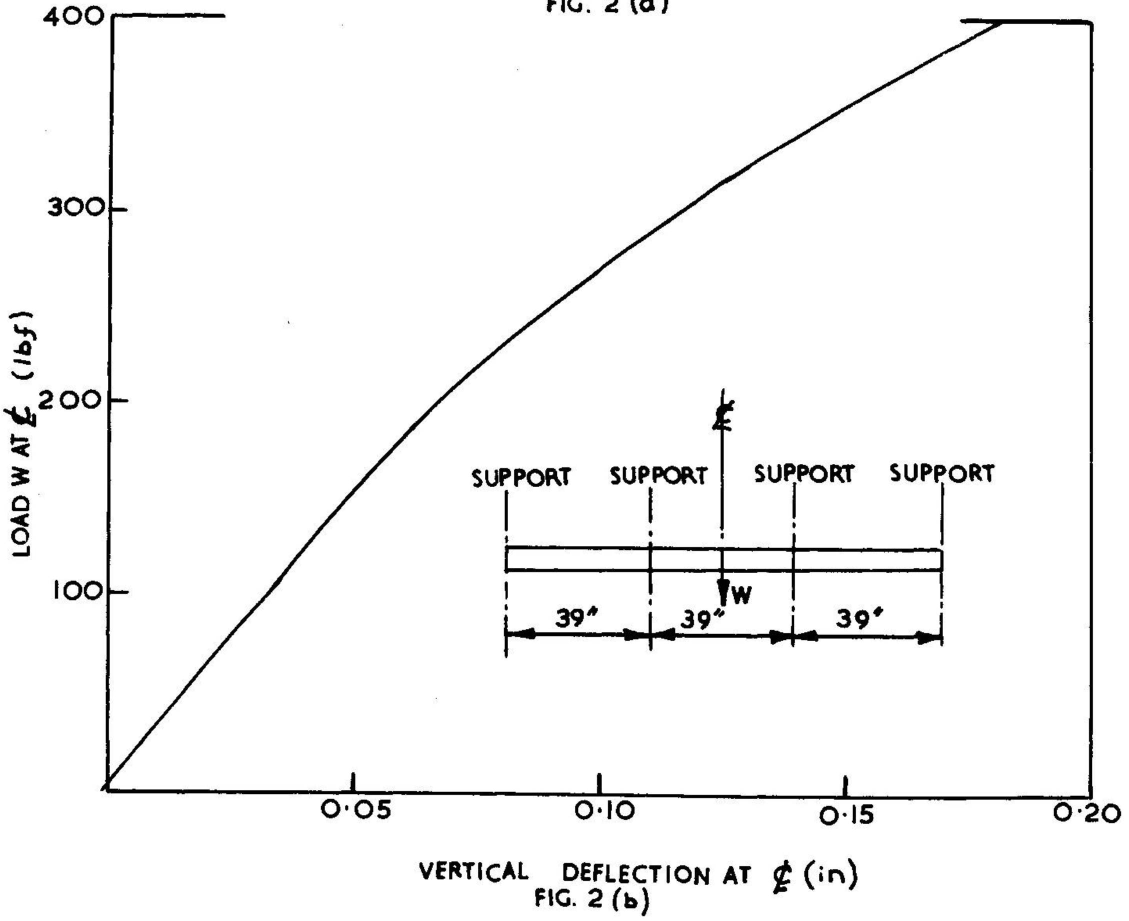

FIG. 2 (b)

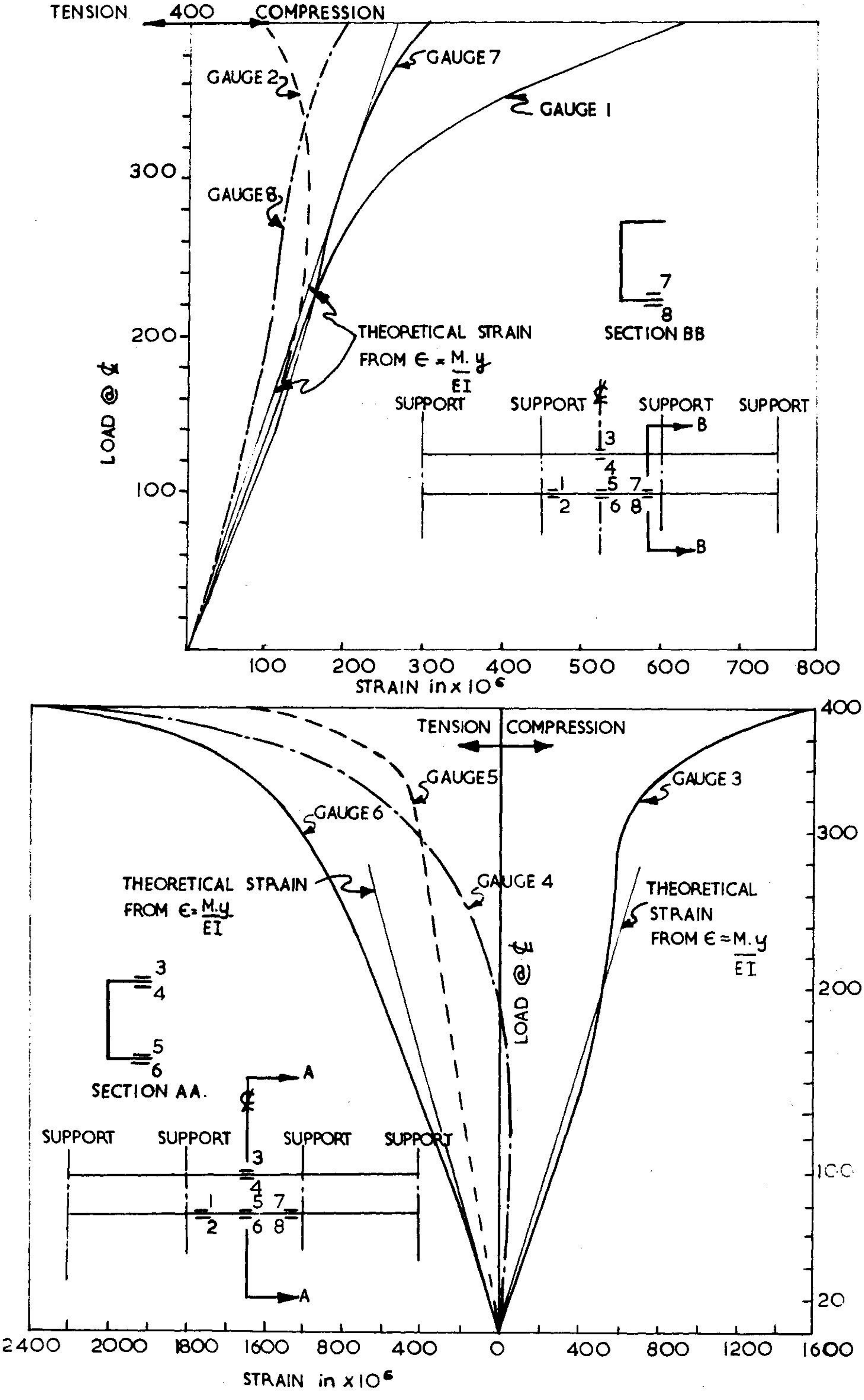
TENSION
400
COMPRESSION
GAUGE 2
GAUGE 7
GAUGE 1
GAUGE 8
300
200
100
LOAD @ ℄
THEORETICAL STRAIN FROM $\epsilon = \frac{M.y}{EI}$
7
8
SECTION BB
SUPPORT
SUPPORT
℄
SUPPORT
SUPPORT
B
3
4
1
2
5
6
7
8
B
100
200
300
400
500
600
700
800
STRAIN in x 10⁶
400
TENSION
COMPRESSION
GAUGE 5
GAUGE 3
GAUGE 6
300
THEORETICAL STRAIN FROM $\epsilon = \frac{M.y}{EI}$
GAUGE 4
THEORETICAL STRAIN FROM $\epsilon = \frac{M.y}{EI}$
LOAD @ ℄
3
4
200
5
6
SECTION AA.
A
℄
SUPPORT
SUPPORT
SUPPORT
SUPPORT
3
4
1
2
5
6
7
8
100
A
20
2400
2000
1800
1600
800
400
0
400
800
1200
1600
STRAIN in x 10⁶

FIG. 3.

Experimental Programme

A series of tests to failure were carried out on 120 inch lengths of 2 inch by 1 inch cold formed mild steel channel sections. Two thicknesses of material were used; 0.025 inches and 0.035 inches. The beams were supported in four diaphragms each 39 inches apart. This gave rise to a three span continuous beam configuration as shown in Fig. 1. The diaphragms prevented vertical and horizontal deflection and twist in the plane of the section.

Loads were applied at the centre of the middle span by means of a disc or plate clamped to the web of the beam. Using a disc with its centre arranged to coincide with the shear centre of the section pure torque about this point was applied.

For bending, loads were suspended from a plate clamped to the web of the section with the weight hanger in the vertical plane containing the shear centre. By carying the lateral position of this weight hanger it was possible to produce the third loading condition, that of combined bending and torsion. Recordings of vertical deflection and angle of twist at the centre of the middle span were taken at each movement of load. In addition strain gauge readings at eight critical flange positions for each load increment, were taken during the 'pure' bending tests. The strain gauges used were of the 'foil yield' type and can measure strains ranging from 10% to 20%.

Experimental Results

i) Pure Bending

As already noted the loading for this form of test was in the plane of the shear centre. It is however appreciated that the reaction forces at the diaphragm supports would not be in this same plane. This would lead to some small increments of torque and resulting twist being present during the tests. In fact as can be seen from Fig. 2 (a) the angle of twist at the centre of the middle span during one of the 'pure' bending tests was approximately 0.016 radians at 220 lbf and 0.1 at 400 lbf. This particular beam finally collapsed at a load of 435 lbf.

In all the 'pure' bending tests the mechanism of collapse was the same. Thus a collapse 'hinge' formed first at the centre of the middle span and then complete failure occurred when two such 'hinges' formed close to the two internal supports. A beam after failure is shown in Fig. 4.(b)

This form of collapse mechanism is similar to that assumed for this case in standard limit analysis theory. The collapse hinges, however, appeared to be the result of gross geometric deformations of the cross-section which result in a reduction of the bending stiffness together with the development of plasticity in the material.

The effect of local bending in the flanges which finally produces local flange buckling is clearly seen from the strain gauge results shown in Fig. 3. At the centre of the middle span local bending of the compression flange commences at the first load increment and increases rapidly with load. In the results shown the underside of the top flange (Gauge 4) had actually gone into tension at half the collapse load (approximately 220 lbf) On offloading from this position the beam returned to its initial state indicating the elastic nature of this local deformation at this stage.

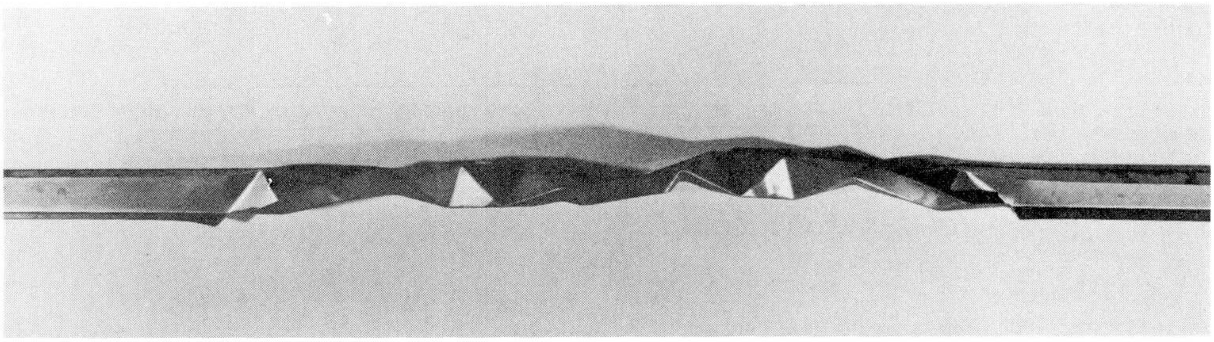

FIG. 4 (a) PURE TORSION COLLAPSE.

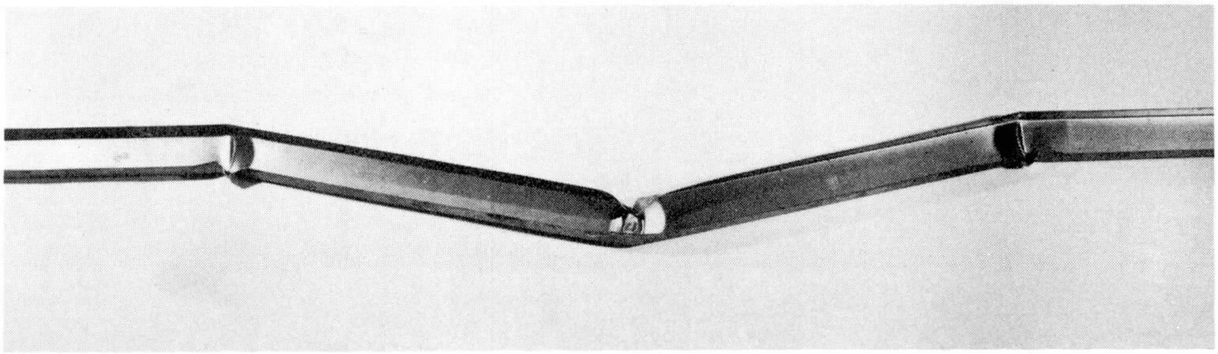

FIG. 4 (b) PURE BENDING COLLAPSE.

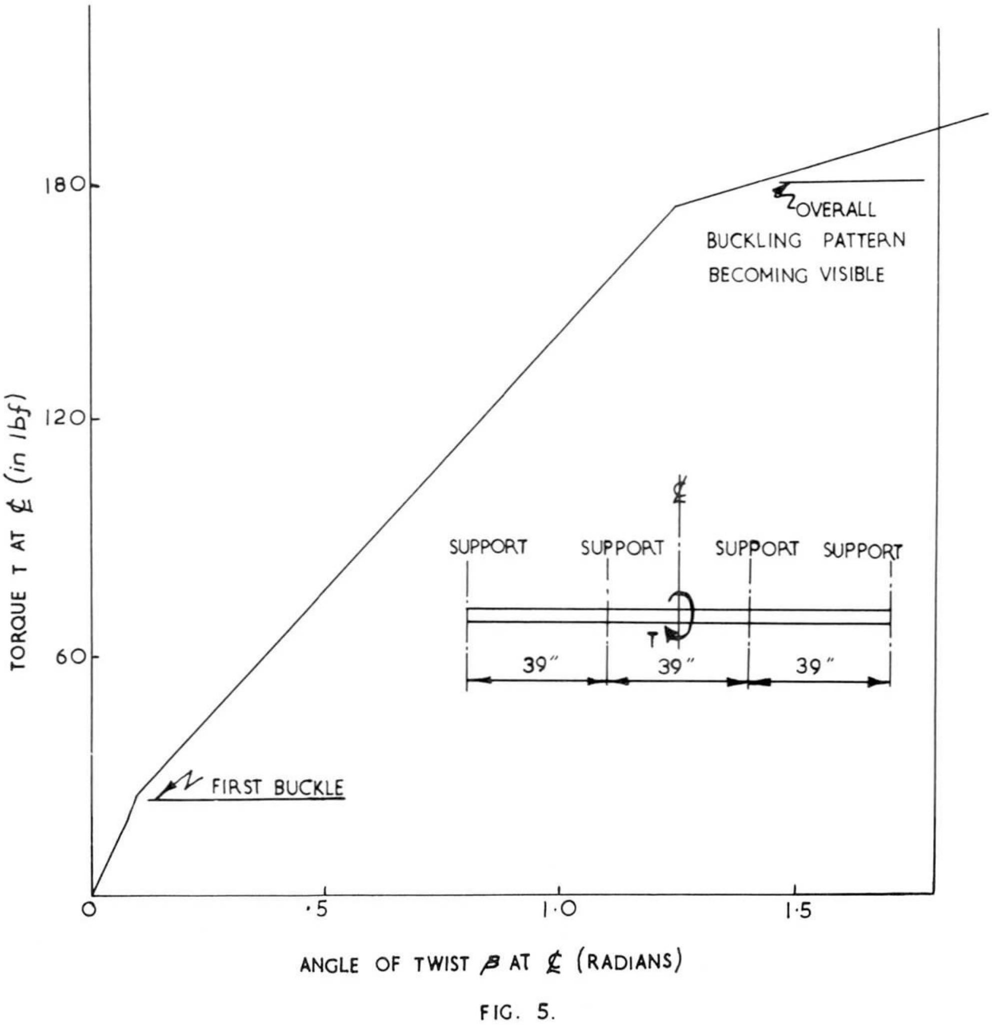

FIG. 5.

As would be expected the effect is much less pronounced in the tension flange (Gauges 6 and 6) and also in the compression flange near the internal supports (Gauges 1, 2, 7 and 8).

The vertical deflection at the local position (Fig. 2 (b)) increased almost linearly until collapse occurred at which stage it increased too rapidly to be recorded. However at a load of 400 lbf, only 35 lnf less than the collapse load, the deflection was as little as 0.18 inches, that is approximately 1/220 of the span.

ii) Pure Torsion

In this series of tests the effect of local buckling was also very pronounced. A typical torque/angle of twist equilibrium path at the centre of the middle span is shown in Fig. 5. Initially a local buckle formed adjacent to the loading disc of a relatively low value of applied torque (24 in lbf). Further increases in torque gave rise to a linear torque/angle of twist relationship until the initial stages of the failure mechanism became apparent (180 in lbf). Thereafter the angle of twist increased rapidly until failure occurred (204 in lbf). At failure the deformations took the form of a very distinct pattern of web buckling. The lines formed by the buckles divided the web of the middle span into a uniform series of triangular areas as shown in Fig. 4(a).

The failure mode was again considered to be a combination of gross geometric deformation of the cross-section and the development of zones of plastic material.

iii) Combined Bending and Torsion

As would be expected the collapsed form of the beams when subjected to combined bending and torsion indicated the same gross geometric cross-sectional deformations and development of plasticity in the material. Theoretically, longitudinal warping stresses due to torsion initiate local flange yielding at lower values of load than in the corresponding 'pure' bending case. However the final collapse loads were not significantly different when the load to produce the combined effects was acting in the vertical plane containing the centroid of the section. This form of loading is perhaps closest to that obtaining in any practical situation using such sections.

Summary and Conclusions

The test results have indicated clearly that final collapse for all three forms of load action resulted from a combination of elastic instability, inplane cross-sectional deformation and some plastic flow. It was obvious that the standard 'plastic hinge' concept was not directly applicable in this case.

As would be expected local flange bending and buckling play a prominent part in the collapse at any section. At critical positions of maximum bending moment and torsional bi-moment, local bending effects are initiated at very small loads. They are not visible at this stage but are easily observed from the strain gauge readings. Such effects become visible at higher loads in the form of a pronounced local buckle. At this stage the magnitude of the local flange deflection is many times greater than the material thickness.

Some typical results from the tests are given in the following table. The first group correspond to 'pure bending' loads and the second to combined bending and small torsion, that is, the loads acting in the vertical plane containing the centroid. The two figures in the last column are the values of load for each group required to develop the yield stress at the centre of the middle span. The values are calculated from linear-elastic analysis and the lower load for the combined actions arises from taking into account the longitudinal warping stresses due to torsion.

Group	First Buckle Load	Collapse Load	Theoretical First Yield Load
1	110 131 141	200 197 219	226
2	191 121 131	226 192 197	91

TABLE 1 (All loads given in lbf)

From this table it can be seen that (i) as already noted there is no significant difference in collapse loads for the two different forms of loading and (ii) although theoretically the warping stresses produce local yielding at lower loads this does not significantly affect the load required for developing the first buckle.

In relation to this latter comment it must be noted that longitudinal warping stress distribution round the cross-section gives a maximum value at the free edge of the flange and reduces rapidly towards the web to flange junction at which point it will have changed sign. A detailed analysis of such stress in thin walled continuous beams subjected to bending and torsion has been presented elsewhere (2,3). However as these effects are highly localised they will tend to give rise to conservative safe loads if used in standard elastic design procedures.

It is possible that by adopting a design procedure based on collapse more economic use can be made of thin walled sections. The obvious difficulty is the prediction of the collapse loads for such sections. The stress distributions for combined bending and torsion are highly non-uniform which makes the evaluation of critical compressive stresses in the flanges very complex. In addition gross cross-sectional deformations which occur locally in flanges prior to collapse are, as already noted, many times greater, than the material thickness. This implies that the flange, considered as a plate element, is in the non-linear behavioural range. Thus, the value of collapse loads are unlikely to be predicted by any method which is based on a linear theory. Local imperfections will also influence the behaviour particularly in the non-linear range.

However the results of tests so far have shown reasonable repeatability of both collapse forms and ultimate loads. They have also indicated a considerable post local buckling load carrying capacity. It does not seem unreasonable therefore that design criteria, which allow for elastic instability, post critical load carrying capacity and some measure of plastic flow, can be developed.

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SUMMARY

This contribution concerns an investigation into the mechanism of collapse of thin walled continuous beams. Three forms of load action are considered; pure bending, pure torsion and combined bending and torsion. All tests were continued until collapse occurred, this condition being defined as the state at which no further load could be carried. Details are given of deflections, angles of twist and strain gauge readings, observed during the tests. The experimental results illustrate the complexity of the failure modes. As a result some indication is given of the factors to be considered in the development of adequate design criteria.

RESUME

Le présent article étudie les modes de ruine des poutres continues à parois minces. On considère trois sortes de sollicitations: flexion simple, torsion et combinaison des deux cas. Tous les essais ont été effectués jusqu'à l'état de ruine, défini par le point où la poutre ne supportait plus une augmentation de charge. On indique en détail les flèches, les angles de torsion et les lectures sur les "strain gauges" durant les essais. Les résultats expérimentaux illustrent la complexité des cas de ruine. En conclusion, on étudie les facteurs importants pour le développement des critères de construction.

ZUSAMMENFASSUNG

Dieser Beitrag schildert die Untersuchungen über die Mechanismen der plastischen Gelenke bei dünnwandigen, durchlaufenden Balken. Drei Lastfälle sind betrachtet worden: Reine Biegung, reine Drillung und die Kombination derselben. Alle Prüfungen sind bis zum Kollaps (Zusammenbruch) durchgeführt worden, der für jenen Zustand definiert wurde, da keine weitere Last mehr angebracht werden kann. Durchbiegungen, Drehwinkel und Dehnungsmesstände während des Prüfverlaufs werden angegeben. Die experimentellen Ergebnisse verdeutlichen die vielfältigen Zusammenhänge der Brucharten. Als Ergebnis werden einige Punkte aufgezeigt, die beim angemessenen Entwurf berücksichtigt werden sollten.