A METHOD OF TESTING REINFORCED CONCRETE T-BEAMS IN COMBINED BENDING, SHEAR AND TORSION

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1. Introduction

Although T-beams are very common in practice, few tests have been reported on their behaviour in combined loading. Furthermore, only few publications deal with *fully reinforced* beams (i.e. with both longitudinal and transversal reinforcement) subjected to the combination of the three types of beam loading: bending, shear and torsion. On the basis of test results, several authors tried to construct interaction surface, but, as yet, only for longitudinally reinforced beams. Even for this relatively simple case (to be considered as a step toward the solution of the complete problem) the reported results scatter too much to be applied in design without verification. The data on testing equipment given in some test reports [1] were of little use because very few of them applied to testing T-beams. The paper by T. T. C. HSU and A. H. MATTOCK "A Torsion Test Rig" was not at the author's disposal at the time of designing the testing setup. On the other hand, an improved arrangement (such as those described by PANDIT and WARWARUK [1] or by CHINENKOV [2] would cause prohibitive costs. Therefore an arrangement was sought for, needing possibly little additional instrumentation. The existing loading setup merely for bending was designed by the research officers of the Department of Strength of Materials and Structures headed by Prof. Dr. GYÖRGY DEÁK in 1974 [3], and was kindly made available to the authors.

The outlined step-wise modifications resulted in the loading arrangement described in the respective item. The original idea was to simultaneously load the two halves of beam through spreader beams whose reactions produce bending moment and torque, respectively, letting the ends of the beam freely twist and rotate (Fig. 1). The position of the hydraulic jack on the spreader beam was defined by the required ratio of bending to torsion moment. This was meant to halve large twisting angles at the unrestrained beam end, likely to disturb controlled application of forces. Namely, in unilaterally restrained beams the transversal force, expected to produce bending moment alone, does contribute to the increase of torque, too; the two equal transversal forces differently increase the torque because of different arms. In somewhat longer beams the angle of twist tilts the beam surface at the point of application of transversal forces resulting in considerable friction forces. The angles of rotation being different at the two points, the friction forces produce unequal torques. Unfortunately, the trial did not work, because practically no perfectly balanced conditions are possible: a slight difference between the torques on the two sides of beam causes the whole beam to rotate around the longitudinal axis passing through the tops of ball bearings. In spite of being aware of all its disadvantages, the authors had to recourse to the one-fixed-side mode of testing. One of the two hydraulic jacks was replaced by a ball bearing supported on a bracket fixed to the loading bed by two screwed rods. All other details of testing arrangement remained unchanged.

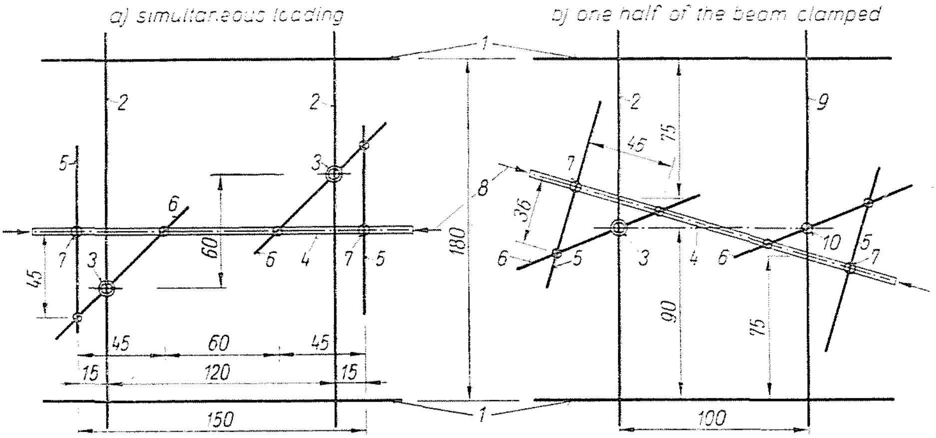

Fig. 1. Loading arrangements in top view. 1. Longitudinal girder of basic setup; 2. Loading frame; 3. Hydraulic jack; 4. Test beam; 5. Clamping rig; 6. Spreader beam; 7. Ball bearing; 8. Steel girder supporting the ball bearings; 9. Clamping bracket; 10. Ball joint (torsional reaction)

But this mode of testing was not successful either. Namely the distributing steel beam failed to provide the necessary rigidity; it acted as a short beam with long cantilever. Large deflection of the cantilever end caused disadvantageous twisting of "fixed" end of the test beam. Furthermore, lateral stability of the steel beam became questionable. While on the load side this beam was modified so that the acting force and reactions always laid in the vertical plane, such a modification on the "fixed" side would cause a further decrease of the rigidity of steel beam. All this induced the authors to apply the loads separately.

2. Testing program

The research subject was the behaviour of fully reinforced T-beams under combined bending, torsion and shear. Being aware of the extensiveness of the task, the scope has been restricted to some parameters mainly influencing the behaviour of beams, such as shear span and moment-torque ratio.

In the case of flexural shear, the most important parameter appears to be the so-called shear span. In Stuttgart tests [4] the limiting shear spans i.e. those where the load capacity is at its minimum and maximum, respectively, have been established. Therefore three ratios of shear span to effective depth, viz.: 1.5, 3 and 6 have been applied. Since the application of torque sets up a state of shear in a resisting member, the torque is expected to affect the above relations. As for the moment to torque ratios, they were chosen so that the results be comparable with those published in literature and, on the other hand, so as to represent the ratios common in practice. So the following M/T ratios were chosen: 0, 0.5, 2, 5, 10 and ∞ (see Table 1). Since torque length ranging from 3.5 to 6 times the effective depth little affects the torque capacity [5], rather than to apply pure torque on a beam of medium length a combination of loads was applied, resulting in a ratio of $M/T = 10$. Similarly, in the case of long beams the M/T ratio was chosen as 10 instead of 0.5 (where the flexural shear is of minor significance).

Table 1

Series	M/T ratio					
A	0	—	2	5	10	∞
B	—	0.5	2	5	10	∞
C	0	0.5	2	5	—	∞

Thereby at least two specimens were tested where the ratio of failure moment in combined torsion, shear and bending to the failure moment in pure bending was greater than 0.5.

All other parameters, such as cross section, concrete strength, amount and distribution of reinforcement, etc. were kept constant.

3. Description of test specimens

All specimens had a T cross section consisting of the web with nominal size of 16 cm × 28 cm and of the flange of 50 cm × 7 cm, the effective depth being 29.5 cm. They belonged to three groups according to the over-all length, corresponding in turn to the chosen shear span. A length of 20 cm at each support of the beam was threaded into clamping rigs through which the torque was applied. The distance from the support to the end of the beam was 25 cm to provide room for anchorage of longitudinal reinforcement. A test beam of medium length is shown in Fig. 2, and the lengths in each of the three beam groups in Table 2.

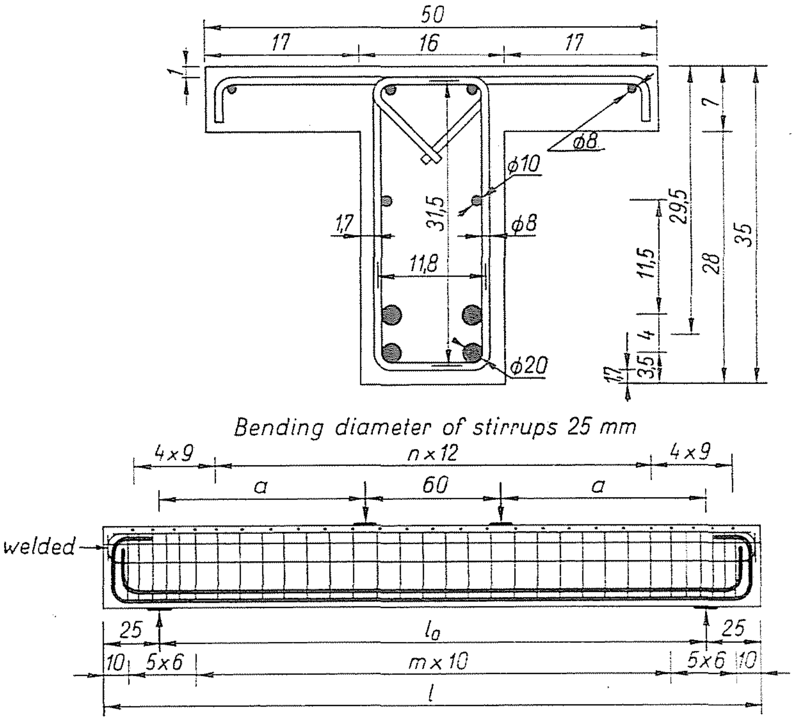

Fig. 2. Properties of test specimens

Table 2

Variable values

Series	Over-all length l (m)	Clear span l_0 (m)	Shear span a (m)	Number of spacings of bars	
				Stirrups m	Flange bars n
A	4.70	4.20	1.80	30	30
B	2.90	2.40	0.90	21	17
C	2.00	1.50	0.45	12	9

Both longitudinal and transversal reinforcement consisted of medium-grade deformed bars with yield strengths from 4100 to 4900 kp/cm². The percentage of bottom longitudinal steel was much higher than that of the top steel to simulate the beams commonly met in practice (especially bridge girders). Closed stirrups were tied to the longitudinal bars by soft steel wire. The flange was reinforced by ∅ 8 mm bars with rectangular hoops spaced at 12 cm. At each end of the beam (over a length of 40 cm), about 50 per cent more transversal reinforcement was applied to avoid local failure in the zone of clamping.

The details of the reinforcement cage are seen in Fig. 2. The concrete mixtures were made of standard Portland cement and Danube sand and gravel of 16 mm maximum size, dosed at a proportion of 1 : 2.26 : 2.76. The aggregate conformed the zone between the Fuller's and EMPA curves according to Yugoslav standards, and the favourable zone as defined by Hungarian standards, respectively. The design cube strength was 280 kp/cm². The slump was 4 to 6 cm. The concrete was compacted by high-frequency internal vibrators. For each beam two or three (depending on its length) batches of concrete were mixed. From each batch one 20 cm side cube (in the case of short beams two cubes), one $12\times12\times36$ cm prism, one $15\times15\times70$ cm prism and one 15 by 30 cm cylinder were made. These control specimens served for determining the compressive strength, the moduli of elasticity (in compression), and of rupture (third-point loading) and the split-cylinder strength, respectively. The beams were cast in plywood forms coated by nylon sheets and the control specimens in steel moulds.

Both beams and control specimens were cured 3 to 5 days under nylon sheets in the forms; after stripping the beams were watered twice a day until seven days of age, while the control specimens were cured under the sheets until that age. Then they were stored and air cured until tested.

4. Test setup and procedure

The test setup is shown diagrammatically in Fig. 3 and illustrated in Fig. 4. The basic loading setup consisted of two longitudinal steel beams supported on two transversal steel girders (loading bed). Two frames bearing hydraulic jacks were screw connected to the longitudinal beams and could be moved along the beams in steps of 20 cm. In the same way the hydraulic jacks could be moved along the top girders of the frames. Four more steel girders of the same size as the top frame girder served for supporting bearings, affixing one end of the test beam etc. The flexural load was applied through 20 Mp hydraulic jacks (VEB Werkstoffprüfmaschinen, Leipzig, GDR) with the exception of the two beams (one short and the other of medium length)

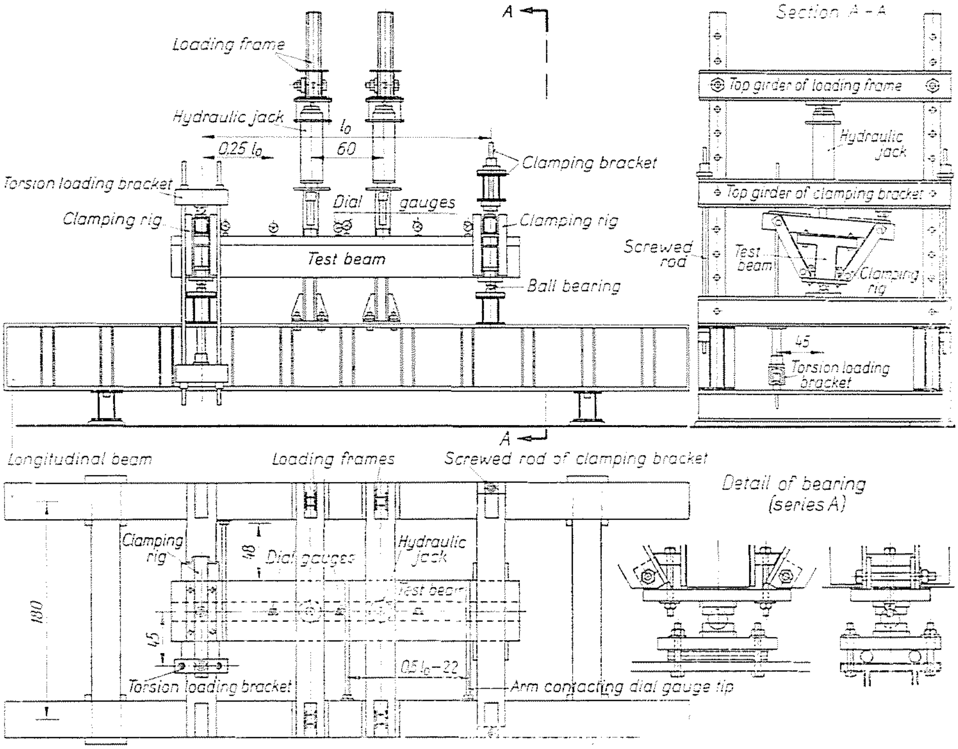

Fig. 3. Test setup and loading arrangement

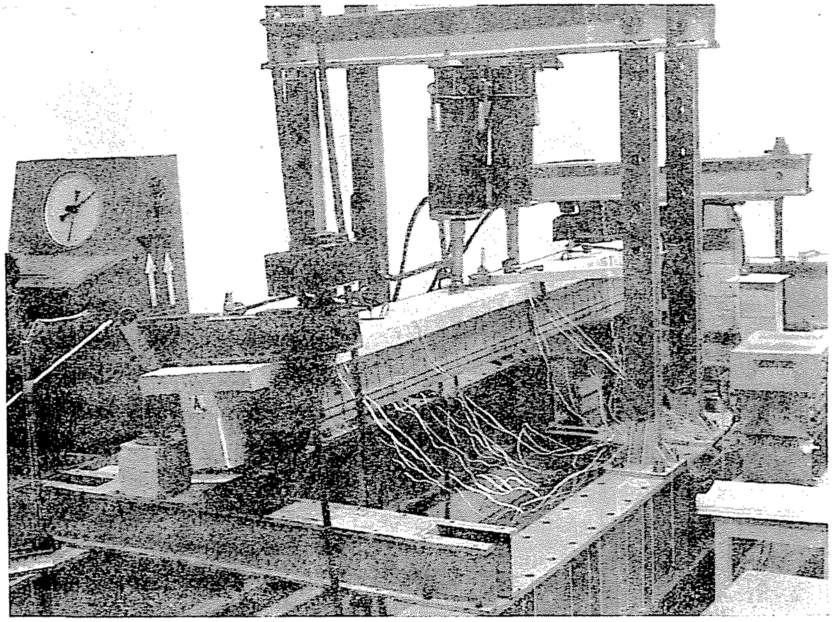

Fig. 4. Typical test arrangement

subjected to bending and shear, in which case the load was applied through 40 Mp center-to-hole hydraulic rams (Lucas, FRG) operated by a motor pump. In that case the intensity of load was measured by a load cell. The lower ends of hydraulic jacks were supported on steel balls in bearings glued by epoxy resin to the roughened surface of concrete to prevent sliding at stages of loading involving great twisting angles. The distance between the jacks was kept constant at 60 cm throughout the testing program. The torque was applied through the clamping rig by using special bracket and 10 Mp center-to-hole hydraulic ram operated by a hand pump. An identical rig was put on the other end of the beam to transfer the reaction of the force producing the torque to the clamping bracket.

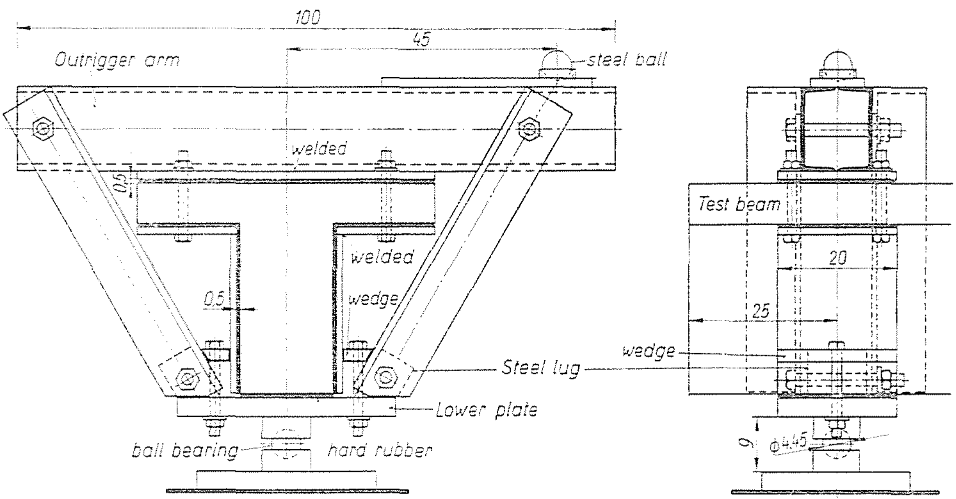

Fig. 5. Clamping rig

The clamping rig (Fig. 5) consisted of the upper rung (outrigger arm) connected with the lower plate by two pairs of L steels. The L steels were connected to the outrigger arm and the steel lugs protruding from the lower plate by screws. On the lower side of the outrigger arm a steel plate of a length equal to the flange width was welded; similar steel plates were applied on the underlying face of the flange and on the faces of the web. Between the plates and the concrete surface a layer of hard rubber was placed to prevent local stress concentrations. The horizontal plates were connected by screws passing through the holes in the flange of the beam, and the vertical ones were tied by wedges, screwed in turn to the lower plate. The lower plate was placed on the ball bearing supported on a steel plate resting on the transversal steel girder. To enable free elongation in bending of the tensile zone of the longer beams, two rollers were placed between the bearing plate and the transversal girder (see the detail in Fig. 3).

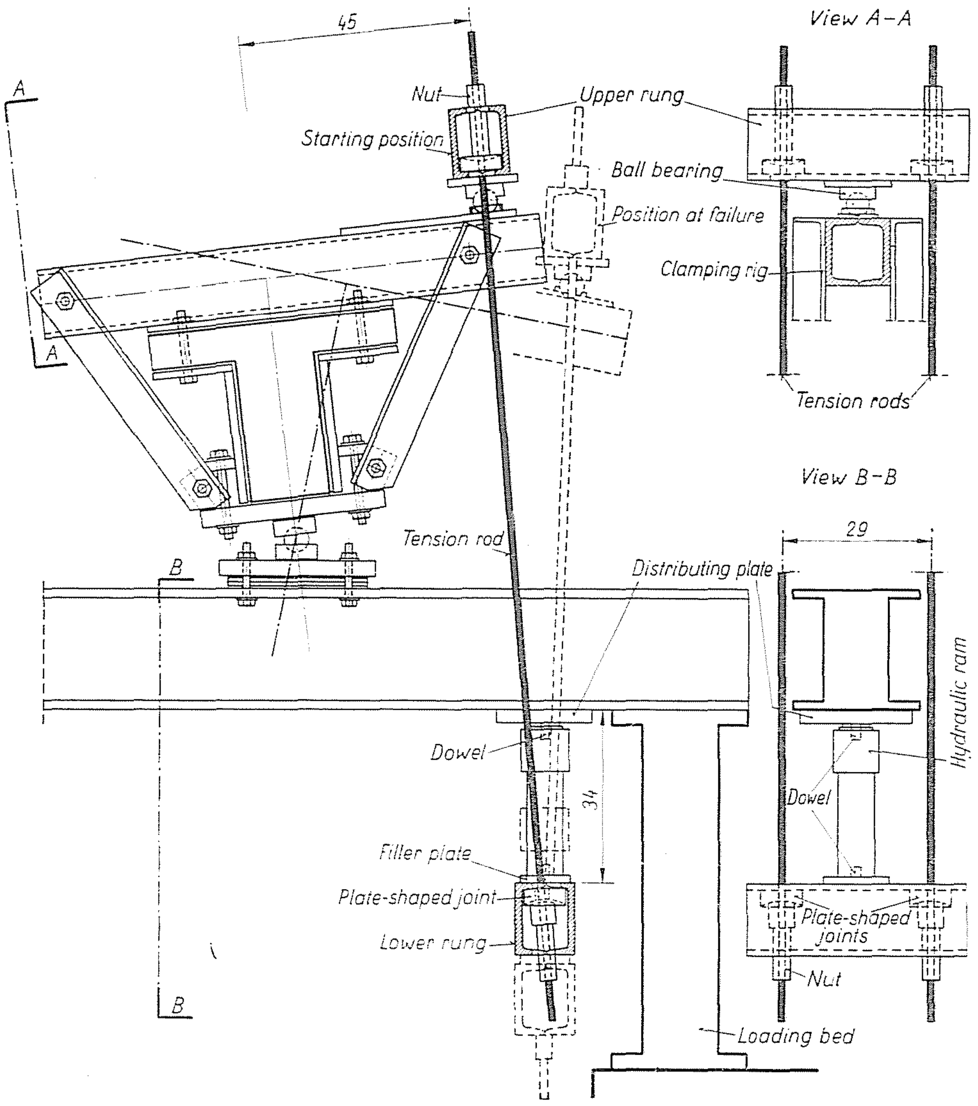

Fig. 6. Torsion loading bracket

The bracket which transferred the reaction of the hydraulic ram to the transversal steel girder of the basic loading setup (torsion loading bracket) is drawn in Fig. 6 and illustrated in Fig. 7. The rungs of the bracket consisted of double [steels intentionally rigid to provide as little deflection of the ends as possible. Two deformed steel bars passing through the bore-holes in the flanges of the rungs served as tension rods. Nuts passed along the helical ribs through the greater holes in the outer flanges. Between the outrigger arm of the clamping rig and the upper rung of the bracket, a ball bearing was applied.

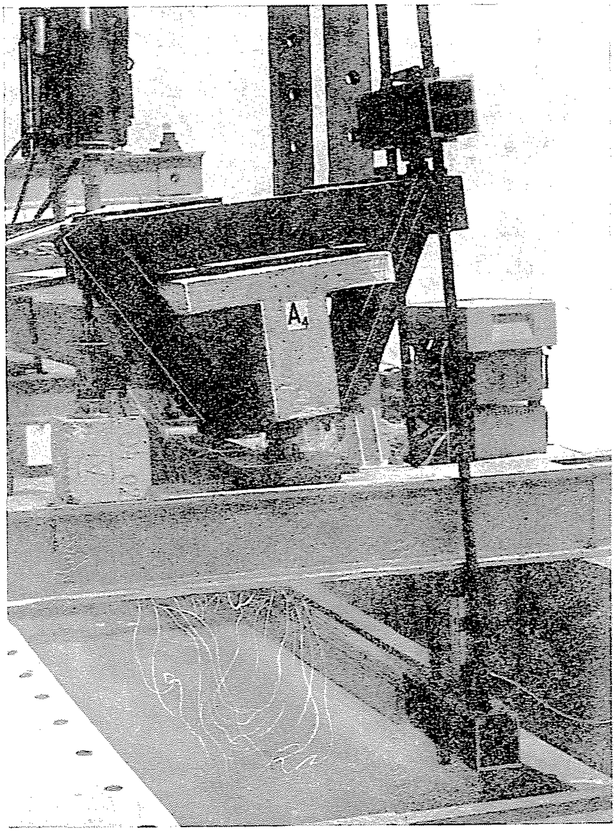

Fig. 7. Photo of torsion loading bracket

On the top face of the lower rung a filler plate was welded. In its centre a cylindrical dowel of 25 by 25 mm was welded to penetrate into a hole in the base of the hydraulic ram.

A distributing plate with a similar dowel which was to penetrate into a hole in the piston of the ram was applied on the underlying face of the transversal steel girder. The two dowels served to prevent lateral shifting of the ram. The lower nuts leaned on the plate-shaped joints to permit necessary rotation of the rods during loading. This, together with the motion of the ram piston, provided compatibility of displacements of the loading point.

The clamping bracket (see Fig. 3) consisted of a pair of transversal girders (belonging to the basic loading setup) and a pair of screwed rods. On the lower girder the support of the test beam was placed. To eliminate the influence of dead weight of the top girder, its reactions were taken by a column composed of concrete control specimens placed near the end of the clamping rig, and by restraining the nut of the nearby rod (on the side opposite to the ball bearing taking the torsional reaction), respectively. To reduce the disturbance from obliquity of the flange surface, the top girder of the clamping bracket was adjusted in such a way that at incipient loading the longitudinal plane of symmetry was inclined to the vertical plane by an angle approximately half the expected twisting angle at failure. (In section A—A of Fig. 3 the test beam is in initial position.)

The load was applied parallelly in at least ten increments (some beams were loaded in more than twenty increments) taking account of the respective M/T ratios up to failure. The increments varied between 6 and 12 per cent of the failure load; smaller increments preceded the onset of cracking and the failure. At each increment the load was kept constant during recording the strains, deflections and crackings. In each series the beams were tested so that the M/T ratio increased from beam to beam (the first beam was tested in pure torsion or with the lowest M/T ratio and the last in bending with shear). This permitted to adjust the intensity of loading producing the torque to the necessary M/T ratio at each load increment, in accordance with the angles of rotation of beam cross section measured on the previous beam. Namely, depending on whether the flange surface was inclined or declined with respect to the loading point, the intensity of load was reduced or increased, with respect to the necessary load intensity for the case of horizontal flange surface. As the travel of the ram piston was limited to 15 cm in the case of long beams where the displacement of the torsion loading point was large at the higher steps of loading, after the piston achieved its travel the beam was completely unloaded. At higher steps of loading the irreversible twist of beam was of such an extent that the lower rung of the bracket hung freely and the top of the ram was at considerable distance from the underlying face of the transversal steel girder. Therefore the nuts were tightened to enable continuation of loading. To prevent tensioning of rods and uncontrolled force effect, the deflections of neighbouring arms contacting dial gauges were controlled.

5. Measurements

At each load stage, except those preceding failure, deflections from which rotations were computed were measured by means of dial gauges reading to 0.001 mm, and strains in the reinforcement and on the concrete surface were recorded by means of a digital strain gauge with a printer (Hottinger and Baldwin Measuring Instruments FRG).

The arrangement of *dial gauges* is seen in Fig. 3. The deflections were measured at six points: at three points on the beam surface (at midspan and quarter-span points) and at three points at the end of the arms (at midspan and beside the clamping frames), projecting 50 cm from the side of the flange, except for the series of shortest beams where the deflections were measured at only three points: in midspan and beside the clamping frames. Shortness of these beams permitted this simplification. In each case the dial gauges were supported in a manner that prevented displacement of their supports due to loading of beam.

The angle of twist could be computed in the following way. The deflection of a beam point in the cross section of the projecting arm and in the midline of the flange surface could be determined with good approximation, assuming the deflection curve to be a second-order parabola passing through the known deflection point at midspan and zero points at supports. The difference between deflection of the beam point and the arm end point divided by their horizontal distance gives the angle of rotation of the cross section. The difference between the angles of rotation of two cross sections divided by their distance gives the angle of twist.

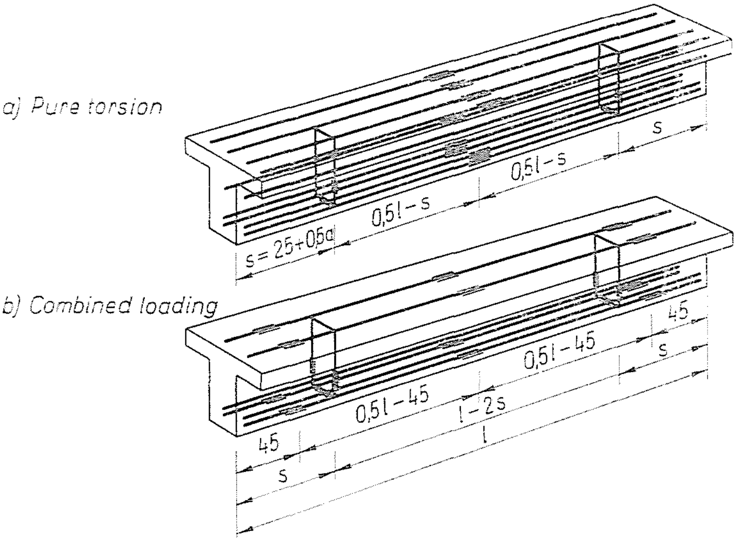

Fig. 8. Arrangement of strain gauges on the reinforcement bars

The electrical resistance *strain gauges* 5 mm in length were bonded on the reinforcement bars according to the schemes shown in Fig. 8. (Because of space shortage, the arrangement of the strain gauges for the beams tested in bending and shear has been omitted; only the lower two longitudinal bars — at midspan and near the bearings — and two pairs of stirrups at shear midspans were strain-gauged.)

Strains on the concrete surface were measured by gauges 67 mm in length, located according to the scheme in Fig. 9. It should be noted that the shortest beams (series C, tested the first) were supplied at every indicated place by two crosswise gauges in order to measure both compressive and tensile principal strains. But these latter were found to be irrelevant after the first crack developed. Therefore in the other series they were oriented in the expected direction of compressive stress and crosswise gauges were applied only in zones where the torsional component of shear stress was not colinear with that of flexural shear. (Again the scheme showing the arrangement of the gauges for the beams tested in bending and shear is omitted; on each face of the web at shear midspan two gauges in the direction of compressive stresses included an angle of 45°.) Both the inner (5 mm) and the outer (67 mm) gauges were produced by the Japanese company KYOWA.

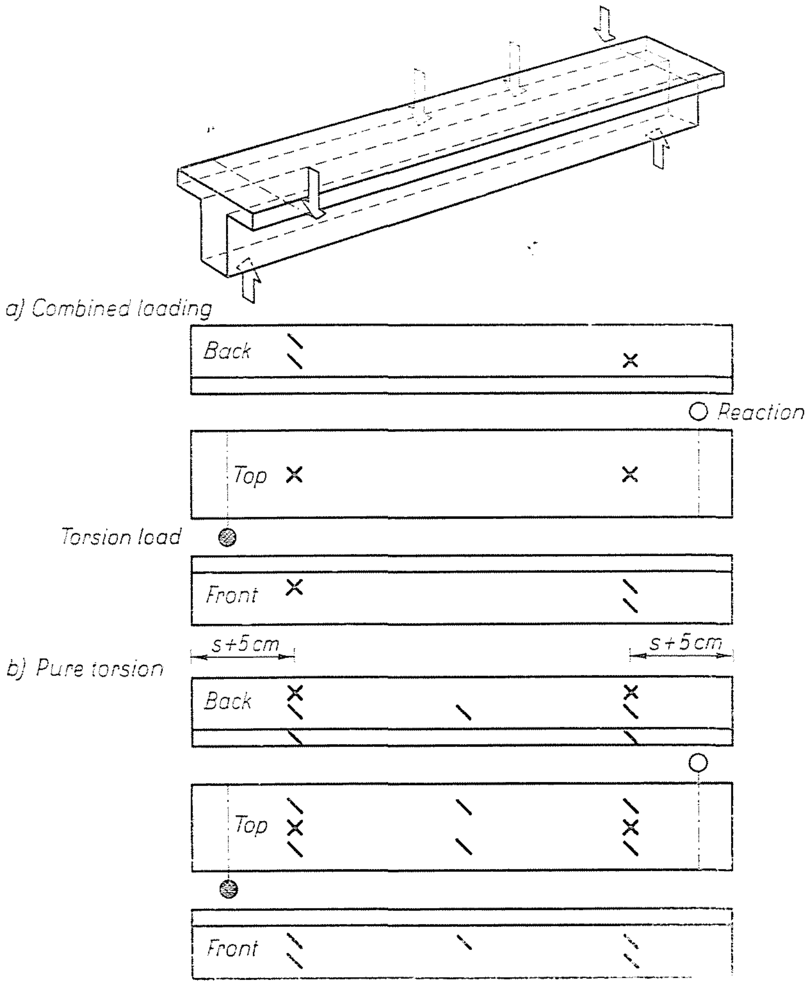

Fig. 9. Arrangement of strain gauges on the concrete surface

The cracks were recorded at each load increment from their onset up to two or three increments preceding failure. After testing, all cracks were outlined in drawing ink and photographed.

6. Conclusion

This paper is intended to be the first part of a test report. The analysis of test results is still in progress and will be published in one of the future volumes. Anyway, to illustrate the necessity of new verifications of existing design provisions, pointed out in the Introduction, the load-bearing capacity, as calculated by using design aids will be compared with some results of these tests.

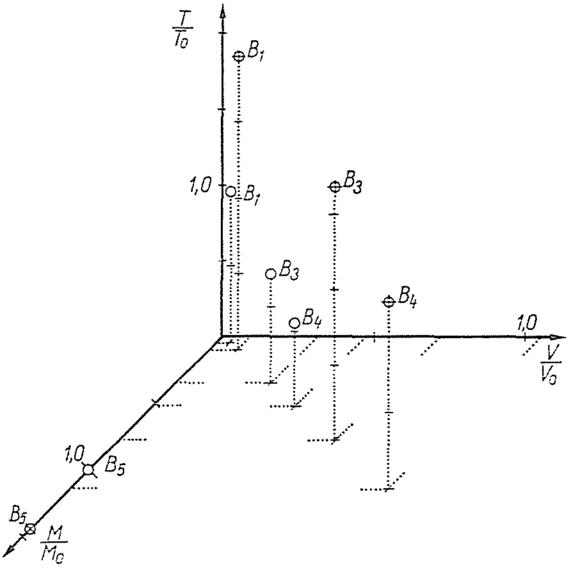

Fig. 10. Comparison of calculated and experimental results for medium-length beams. ⊖ = calculated; ○ = experimental

The comparison will be visualized in a three-dimensional co-ordinate system whose axes represent relative torque, bending moment and shear force, respectively (Fig. 10). The relative torque is the ratio of torque T at given load combination to pure torsional strength T_0 as calculated according to ACI 318–71 provisions [6]. Likewise, the relative bending moment is the ratio of bending moment M to pure flexural moment M_0 at failure, and the same applies to the relative shear force V/V_0.

All test results are seen to greatly exceed the calculated values, even for the beam tested in bending with shear where the failure was of the bending type.

This latter might be due to strain hardening of reinforcement, the "excess" of strength in specimens tested in combined loading could, however, not be explained by this phenomenon alone, a fact testifying the necessity of the performed experimental work.

Summary

The behaviour of fully reinforced T-beams (with both longitudinal and transversal reinforcement) was tested in combined bending, shear and torsion. The use of an adequate loading setup would cause prohibitive costs. Therefore a loading setup has been designed needing a minimum of additional instrumentation to the existing loading setup designed for testing beams in bending with shear. A detailed description of test specimens, procedure and measurements is given. Finally, some test results are compared with the load-bearing capacity as calculated according to ACI 318-71 provisions.

References

1. *Torsion of Structural Concrete*, Special Publication No. 18, American Concrete Institute, Detroit, 1968.
2. Чиненков, Ю. В.: Исследование работы железобетонных элементов при совместном действии изгиба и кручения. *Исследование прочности элементов железобетонных конструкций*, Труды Научноисследовательского института бетона и железобетона, Выпуск 5, Москва 1959.
3. *A Budapesti Műszaki Egyetem Építőipari Laboratóriuma:* Paper distributed at the Inauguration of the Laboratory for Building of the Technical University, Budapest, April 15, 1975.
4. Leonhardt, F.—Walther, R.: Beiträge zur Behandlung der Schubprobleme im Stahlbetonbau, *Beton- u. Stahlbetonbau*, 1961, 1962.
5. Victor, D. J.—Ferguson, P. M.: Reinforced Concrete T-Beams Without Stirrups Under Combined Bending and Torsion, *ACI Journal*, V. 65, No. 1, Jan. 1968.
6. Rajagopalan, K. S.: Design Aids for Torsion Design per ACI 318—71, *ACI Journal*, V. 70, No. 12, Dec. 1973.

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