Shear strength of reinforced concrete beams loaded through framed-in cross-beams

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Objekttyp: **Article**

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

Band (Jahr): **6 (1960)**

PDF erstellt am: **26.05.2024**

Persistenter Link: https://doi.org/10.5169/seals-6946

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Shear Strength of Reinforced Concrete Beams Loaded Through Framed-in Cross-Beams

Résistance à l'effort tranchant des poutres en béton armé chargées par l'intermédiaire de traverses

Die Schubfestigkeit von Stahlbetonbalken mit Lastübertragung mittels Querbalken

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In practically all tests on the shear strength of reinforced concrete beams the loads are applied through rollers and plates direct onto the top surface of the test beam. Likewise, the beam supports are in contact with the bottom surface of the beam. In such a case a local vertical compression may be introduced by the loads and the supports. On the other hand, in the majority of structures the actual loads on a major beam are applied through the medium of cross-beams framing into the main beam.

In a paper published since the Fifth Congress was held, FERGUSON [1] drew attention to this difference in the method of transfer of loads, and suggested that this influences the shear strength of a beam. Such an influence, if it is a real factor, would be of vital importance in view of the difference between the laboratory tests and the actual conditions in a structure, particularly since empirical design data are based on "direct" loading tests. A further study is, therefore, believed to be of considerable importance.

FERGUSON compared experimentally the behaviour of "directly" loaded beams (of the conventional laboratory type) and beams supported and loaded by cross-beams integrally connected with the main test beam. The beams were rectangular, without web reinforcement, and were tested under third-point loading, with the ratio of the shear span to the effective depth, a/d, equal to 1.35. When the load was applied through the cross-beams, or when the beam was supported by the cross-beams, the ultimate load was 38 per cent of the ultimate load of a similar beam loaded and supported direct. When both the loads and the supports acted through the cross-beams the strength of the beam was lower still: 31 per cent of the strength of a beam loaded and supported direct.

This large difference in the strength was ascribed by FERGUSON [1] to the restraining effect of the direct vertical compression induced by the loads and the supports when applied direct to the surface of the test beam. As a further indication of this effect he reported [2] a test on a beam with a cut-away top half over the support: despite this artificially weakened end section the diagonal tension crack opened further away from the support. This behaviour was interpreted to prove the existence of vertical compression forces near the reaction. It should be observed, however, that the a/d ratio of this beam was 3.4, and the position of the diagonal tension crack and the mode of failure are typical of the shear-tension type of failure encountered in beams with this order of the a/d ratio.

Furthermore, it has been shown that at loads approaching the ultimate, shear-tension results in the beam acting as a two-hinged tied arch: in the vicinity of the supports the inclined compression in concrete acts a little above the tension steel, and the concrete higher up is subjected to tension [3]. The Authors have in fact measured tensile strains in the top surface of a beam in the vicinity of the supports. Likewise, MORROW and VIEST's [4] beam No. B 28 E 4, referred to in more detail below, when subjected to a load of 85 per cent of the ultimate, exhibited tensile strains in the top surface over the support, within a distance approximately equal to the effective depth of the beam. It seems, therefore, that the absence of the cut-away part in FERGUSON's [2] beam would be of no consequence.

In any case, the restraining effect is not likely to extend along the beam more than a distance equal to half its effective depth, or possibly even less. An indirect confirmation of this can be obtained from MORROW and VIEST's [4] tests on centrally loaded stub beams (without web reinforcement), in which strains in the tension steel and on the compression surface of the concrete were measured along the shear span.

For example, in their beam No. B 28 E 4, before the first diagonal tension crack has formed, the steel strains increased gradually from the support toward the face of the stub through which the load was being applied. The strains in the concrete also increased gradually up to within some $2^1/_2$ inches (i. e., $^1/_6$ of the effective depth of the beam) of the face of the stub; a sudden increase in strain took place there, and the concrete strain was of higher value up to the face of the stub.

With increase in load, the diagonal tension crack formed but the load on the beam could be doubled before collapse occurred. When the load was 85 per cent of the ultimate, the strain in steel was constant over the entire length of the shear span, this indicating that a horizontal splitting of the concrete at the level of the steel, with a consequent loss of bond, had taken place. The strains in concrete still increased gradually up to within 7 inches of the stub face, and then more rapidly, with a very high strain in the last $2^1/_2$ inches.

In the vicinity of the end reactions, which supported the beam over a 4 inch length, no effects were observed either in steel or concrete strains. Since the effective depth of the beam was 14.5 inches the restraining effect seems to extend over barely half the effective depth of the beam, and appreciably so only over a quarter of the effective depth within the face of the stub. In the vicinity of the end reactions the effect seems to be almost non-existent.

The apparent influence of the method of transfer of the load on the shear strength of a beam requires, therefore, further investigation, and to this end the Authors have tested a series of rectangular beams 4 in. by 8 in. deep with the a/d ratio of 2.1, the loads being applied in various ways.

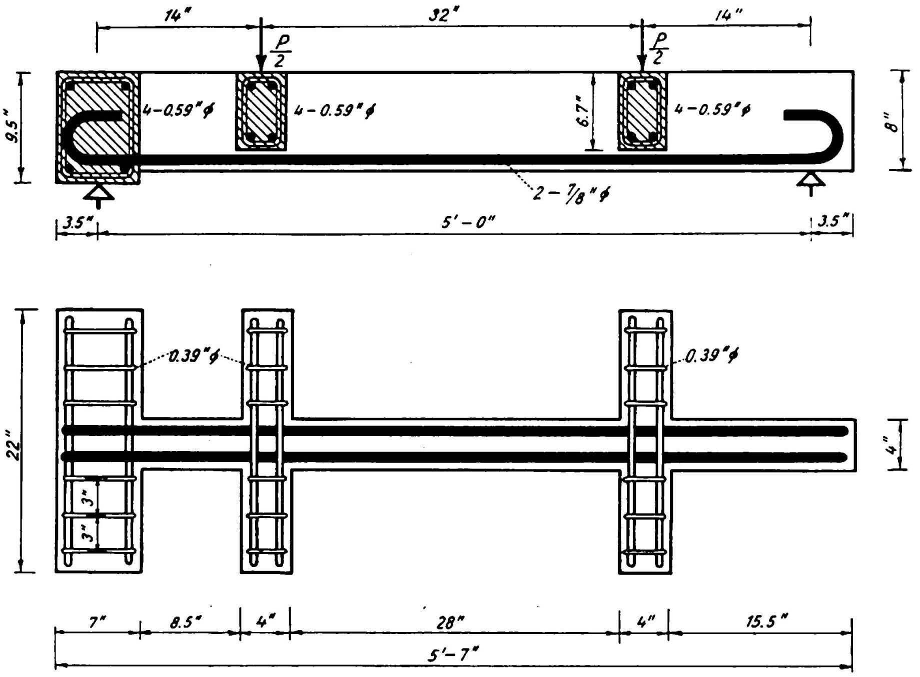
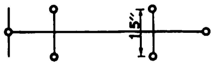


Fig. 1.

All the beams, however loaded and supported, were of the same shape, as shown in fig. 1, and had the steel area ratio, p, of 4.47 per cent, and the effective depth of 6.8 in. A prismatic beam (without cross-beams) was made for comparison purposes, and it was found to have a slightly lower load-carrying capacity than the beam of fig. 1, when loaded and supported direct. This is probably due to the higher second moment of area of the beam with the cross-beams resulting in smaller deflexions and thus lesser opening of the diagonal tension crack.

The test results are summarised in table 1. Considering six beams made with the same concrete, it can be seen that when the loads were applied through cross-beams the ultimate load was between 87 and 92 per cent of the

Table I

Beam No.	Method of application of load	$\frac{a^{(+)}}{d}$	$f_{cu}^{(++)}$ psi	p per-cent	P_c kips	v_c psi	$\frac{v_c}{f_{cu}}$	P_u kips	v_u psi	$\frac{v_u}{f_{cu}}$	P_u as a percentage of beam loaded and supported direct	Mode of failure
1,2		2.09	2225	4.47	16.00	348	0.156	21.52	467	0.210	100	Destruction of beam end at direct support.
3,4		2.09	2090	4.47	13.80	300	0.144	18.64	405	0.194	87	Splitting along the diagonal tension crack in the secondary beam and the main beam and the destruction of the beam end at the direct support.
6		2.09	2280	4.47	12.16	264	0.116	19.88	432	0.189	92	Extension of inclined cracks in the secondary beams into the main beam, leading to the destruction of the beam end at the direct support.

7		2.09	2280	4.47	12.14	264	0.116	18.78	408	0.179	87	Inclined cracks in the secondary beams leading to splitting of the main beam along the diagonal tension crack between the secondary beam load point and secondary beam support.
5		2.09	3780	4.47	13.90	302	0.080	26.66	580	0.154		Inclined cracks in secondary beams connecting with crack in the main beam and leading to splitting of the beam along the diagonal tension crack between the load point and secondary beam support.
8		2.09	3780	4.47	14.36	312	0.082	24.30	528	0.140		Splitting of the beam along the diagonal tension crack between the secondary beam load point and direct support; extension of the crack at a flat slope beyond the load point and into the cross beams

Notes: (+) a measured centre to centre of cross beams.
(++) compressive strength measured on 5″ cubes.
v_c = nominal shearing stress at formation of first diagonal tension crack.
v_u = nominal shearing stress at failure.
P_c = load on beam at formation of first diagonal tension crack.
P_u = load on beam at failure.

load on a similar beam subjected to direct loading. For a pair of beams made with concrete of a somewhat higher strength, approximately the same ultimate load was observed when the load was applied direct (beam No. 5) and when transmitted through the cross-beams (beam No. 8). The ultimate strength of these beams was higher than that of similar beams made with weaker concrete; for this reason table 1 does not include the percentage values of P_u for beams Nos. 5 and 8.

It is important to note that of the four beams which were supported by a cross-beam at one end and directly at the other, two failed in the part of the beam nearest to the cross-beam support (beams Nos. 5 and 7), while the remaining two beams failed near the direct support (beams Nos. 6 and 8). In particular, beam No. 5, loaded direct, failed near the cross-beam support, while beam No. 8, loaded through cross-beams, failed near the direct support. These beams are shown in figs. 2, 3 and 4. Since the load on all beams was applied symmetrically, and half of them failed in the shear-span nearest to either type of support, this behaviour is not believed to confirm the existence

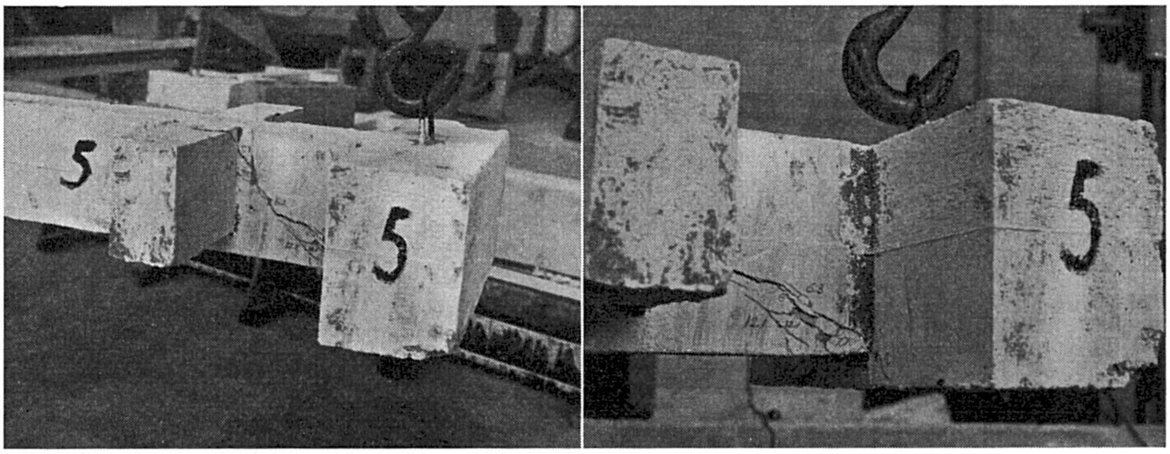


Fig. 2.

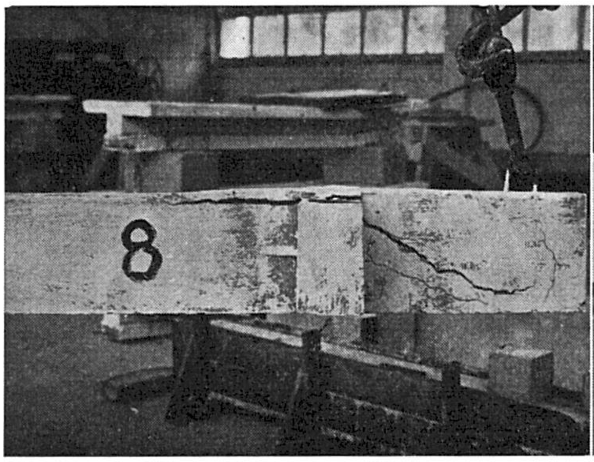


Fig. 3.

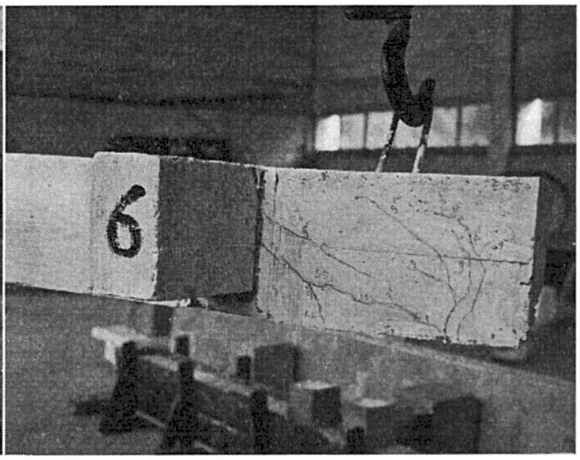


Fig. 4.

of any *inherent* greater strength of a direct support as compared with a support by means of cross-beams.

It is possible, however, that the slightly lower strength of beams loaded by means of cross-beams is due, at least in part, to the cracks in the cross-beams connecting with the diagonal tension crack in the main beam and thus weakening it. An examination of the crack patterns in the shear span nearest to the cross-beam support has shown that in some beams the inclined cracks formed first in the supporting cross-beam, but they immediately extended into the main beam, leading to collapse. However, these cracks may spread in either direction. For instance, in beam No. 6 (fig. 4) the cracks in the cross-beams spread into the main beam, causing collapse in shear-tension. On the other hand, in beam No. 5 (fig. 2) inclined cracks in the cross-beams formed as an extension of the upper end of the diagonal tension crack in the main beam. Failure occurred in shear-tension when inclined cracks formed in the supporting beams between their underside and the level of the tension steel in the main beam; simultaneously, a flat-slope crack formed in the top part of the cross-beam as an extension of the diagonal tension crack in the main beam. The details of the crack patterns in the other beams are listed in table 1.

The cracks in the cross-beams occurred despite the fact that the cross-beams were reinforced in tension and were also provided with stirrups, as shown in fig. 1. It is likely that the lack of stirrups may account for the low strength of FERGUSON's beams loaded through the cross-beams. A well-designed and executed connexion between the secondary beams and the main beam is, of course, essential so that neither the bending nor the shearing stresses produce cracking near the junction of the beams. Details of such recommended connexions are represented in fig. 5.

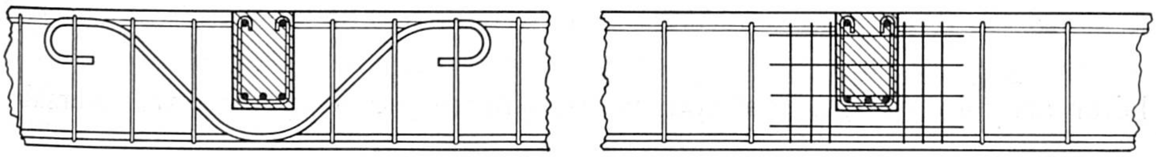


Fig. 5.

The tests described are clearly limited in scope but they show that the restraining effect is considerably smaller than may have been thought from earlier publications. The limited range of the restraining effect is also confirmed by the Authors' interpretation of MORROW and VIEST's [4] tests. Finally, it is believed that this paper may be instrumental in allaying some of the uncertainty concerning the application of results of laboratory tests on beams loaded directly to the design calculations of the shear strength of reinforced concrete beams.

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Summary

Rectangular beams were tested to failure in shear by means of loads and reactions applied direct onto the surface of the beam and through the medium of cross-beams framed into the main beam. From these tests it appear that the use of cross-beams does not result in an appreciable lowering of the load-carrying capacity of a beam, as suggested in some previous reports This is of interest since experimental data are usually obtained from beam loaded direct while in many actual structures the load is transmitted through framed-in cross-beams.

Résumé

On a fait des essais à la destruction par l'effort tranchant sur des poutres rectangulaires, chargées et appuyées soit directement sur la surface de la poutre soit par l'intermédiaire de traverses jointes monolithiquement à la poutre principale.

Ces expériences montrent que le chargement par l'intermédiaire de traverses ne diminue pratiquement pas la limite de charge de la poutre, contrairement à ce que l'on avait prétendu auparavant. Cette conclusion est fort intéressante, car d'ordinaire les résultats des expériences de laboratoire sont acquis sur des poutres chargées directement, tandis que dans les constructions en béton armé les charges sont souvent transmises par des poutres transversales

Zusammenfassung

Es wurde die Schubfestigkeit von rechteckigen Stahlbetonbalken geprüft für den Fall, daß die Lasten und die Reaktionen direkt am Balken angreifen bzw. für den Fall, daß dieselben durch Querbalken übertragen werden. Bei diesen Versuchen zeigte sich, daß bei Lastübertragung mittels Querbalken keine nennenswerte Verringerung der Balkentragfähigkeit eintrat, entgegen den Resultaten anderweitiger Versuche. Dies ist von besonderem Interesse da Versuche in der Regel mit direkt belasteten Balken durchgeführt werden während in der normalen Baupraxis die Last oft mittels Nebenbalken übertragen wird.