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Shear in Structural Concrete: a Reappraisal of Current Concepts

Cisaillement du béton armé: nécessité de reconsidérer les concepts courants

Schubtragfähigkeit: Fragwürdige Bemessungsgrundlagen

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SUMMARY

Evidence is presented which demonstrates that current design concepts are incompatible with the ultimate limit state of reinforced concrete beams. It is found that shear capacity is associated with the strength of the compressive zone and not, as widely considered, the portion of the beam below the neutral axis. The mechanism of shear resistance and the causes of failure are identified and it is shown that modelling a reinforced concrete beam as a frame with inclined legs tied by the tension reinforcement can lead to reliable design solutions which are both more economical and safer than those resulting from current design models. It is suggested that any skeletal structural form can be considered as an assemblage of elements formed between consecutive points of inflection with the elements being described by the proposed model.

RÉSUMÉ

La preuve est établie que les concepts courants de dimensionnement sont incompatibles avec l'état de limite ultime des poutres en béton armé. La résistance au cisaillement est en réalité associée à la résistance de la zone comprimée et non pas à la zone située au-dessous de l'axe neutre, comme couramment considéré. On décrit ainsi le mode de résistance au cisaillement, de même que les causes de rupture; une poutre en béton armé modélisée par un cadre aux bords inclinés et reliés par l'armature de traction peut mener à des solutions de dimensionnement fiables qui sont bien plus sûres et économiques que celles résultant des modèles de conception courants. On suggère donc de considérer toute forme d'ossature comme un assemblage d'éléments décrits précédemment se formant entre deux points d'inflexion consécutifs.

ZUSAMMENFASSUNG

Versuchsergebnisse über die mangelhafte Beschreibung des Stahlbetonverhaltens mittels derzeitiger Bemessungsgrundlagen werden vorgetragen. Es wird gezeigt, dass die Schubtragfähigkeit nicht, wie üblich angenommen, dem unterhalb der Nullinie liegenden Balkenanteil zugeordnet ist, sondern der Tragfähigkeit der Betondruckzone. Der Mechanismus des Querkraftwiderstands und die Fehlerursache werden ermittelt. Es wird anschaulich vorgeführt, dass die Abbildung des Stahlbetonbalkens durch einen Rahmen mit schrägliegenden Beinen und Zugband zu zuverlässigen Bemessungslösungen führen, die nicht nur wirtschaftlicher, sondern auch sicherer als die Lösungen mittels derzeitiger Bemessungsgrundlagen wie Fachwerkträger und Druckstab mit Zugband sind. Es wird vorgeschlagen, das Stahlbetonskelett als Zusammenstellung solcher Elemente zwischen den aufeinanderfolgenden Momentennullpunkten zu betrachten.

1. INTRODUCTION

Current methods used for shear design often yield poor predictions of shear capacity. Fig. 1 provides an indication of such predictions and demonstrates the possibility for current Code provisions [1-5] to yield predictions which can be over-conservative in certain cases and unsafe in others. Clearly, the cause for such predictions should be attributed to the underlying concepts, common to all current shear design methods, rather than the various formulations used by particular methods for the implementation of the concepts in design.

In view of the above, it is considered that a reappraisal of the current design concepts should be a prerequisite for any future Code revision. Such a reappraisal, which is essential not only for improving existing design models but also, if necessary, for developing new ones, has formed the subject of recent work which has been aimed at identifying the fundamental causes of the observed behaviour of structural concrete members. The paper summarizes the main results of the work and describes a first attempt to implement them in design.

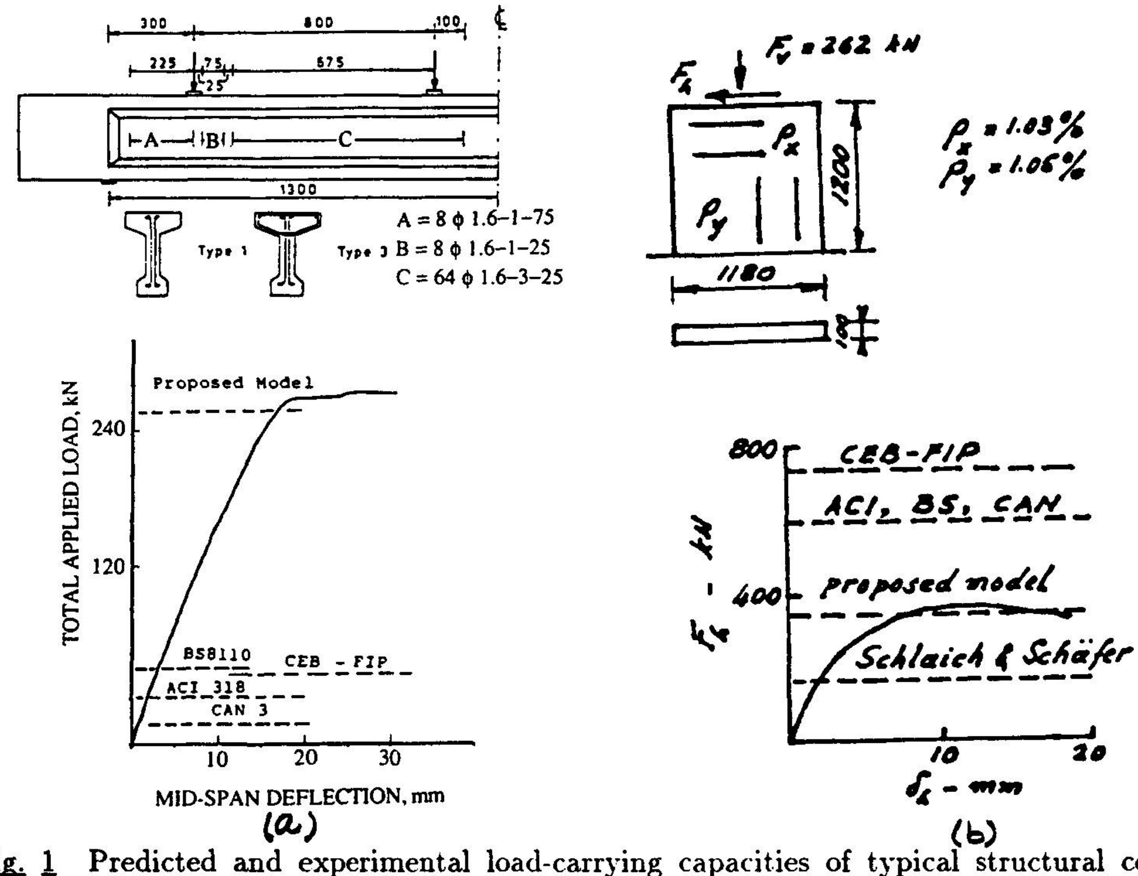


Fig. 1 Predicted and experimental load-carrying capacities of typical structural concrete members tested by (a) Kotsovos & Lefas [11] and (b) Maier & Thurlimann [12].

2. CONCEPTS UNDERLYING SHEAR DESIGN

Current methods for the design of structural concrete members are invariably based on the view that shear resistance is mainly provided by the portion of the member outside the compressive zone. In the absence of transverse reinforcement, such resistance is provided by concrete with main contributor the aggregate interlock which is effected by the shearing movement of the surfaces of inclined cracks. Shear failure is considered to occur when the shear capacity of a critical section is attained and, in order to prevent it, transverse reinforcement is provided to carry the portion of the shear force that cannot be sustained by concrete alone. Such reinforcement is designed on the basis of the assumption that the interaction between concrete and reinforcement can be described by a suitable strut and tie or truss model the strength of which may or may not rely on the contribution of aggregate interlock. In the former case, the model struts are considered to intersect the inclined cracks - and, hence, aggregate interlock is essential for the load-carrying capacity of the struts -

whereas in the latter, a strut is considered to be formed by concrete between consecutive inclined cracks.

3. TEST OF VALIDITY OF CONCEPTS

A test of the validity of the above concepts has been based on an investigation of the behaviour of RC beams, with various arrangements of transverse reinforcement (see Fig. 2a), subjected to two-point loading with various shear span to depth ratios (a_v/d) [6]. The main results of this programme are also given in Fig. 2a in the form of load-deflection curves for the beams tested.

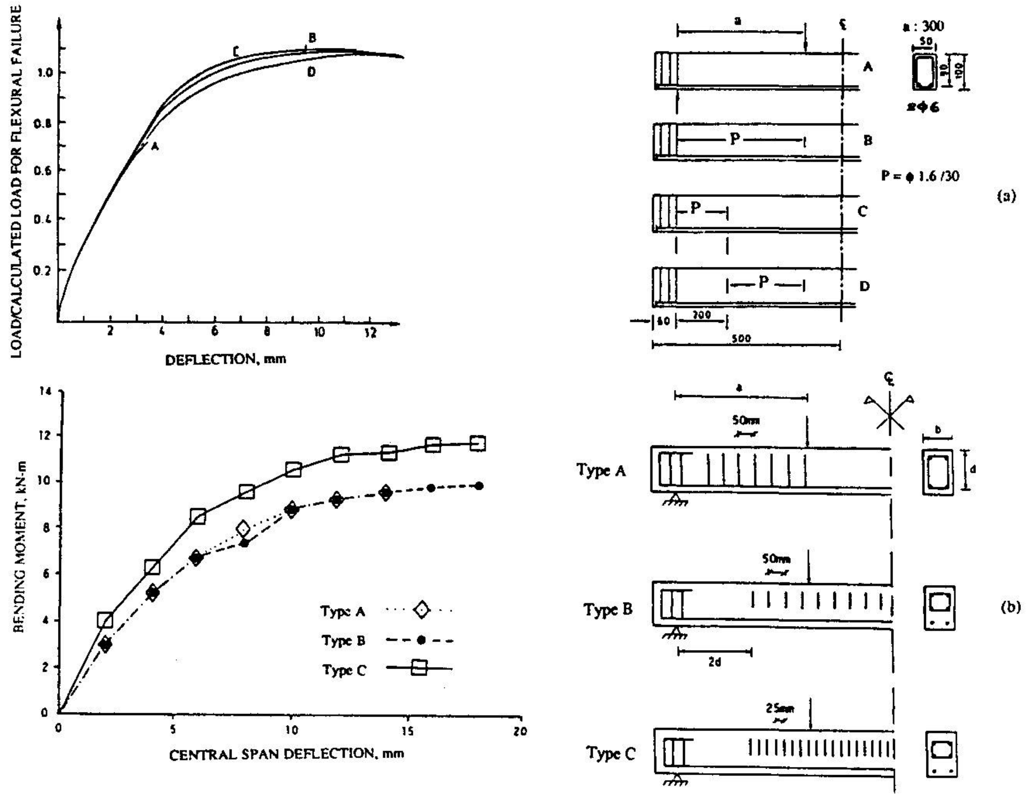


Fig. 2 Typical load-deflection relationships for beams with various stirrup arrangements tested by (a) Kotsovos [6] and (b) Kuttab [8].

On the basis of the concept of shear capacity of critical sections all beams with their shear span without transverse reinforcement, either throughout or over a large portion of its length, should have a similar load-carrying capacity. And yet, beams C and D were found to have a load-carrying capacity significantly higher than that of beams A. In fact, beams C and D exhibited ductile behaviour - a characteristic of under-reinforced concrete beams exhibiting a flexural mode of failure - and their load-carrying capacity was double that of beams A. These results clearly indicate that such behaviour cannot be explained in terms of the concept of shear capacity of critical sections.

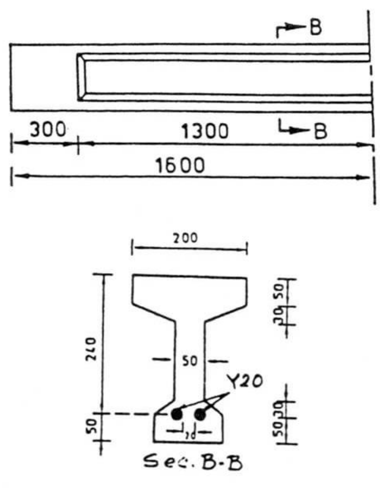
The evidence presented in Fig. 2a also contrasts the view that aggregate interlock makes a significant contribution to shear resistance. This is because the large deflections exhibited by beams C and D led to a large increase of the inclined crack width and thus considerably reduced, if not eliminated, aggregate interlock. In fact, near the peak load, the inclined crack had a width in excess of 2 mm which is by an order of magnitude larger than that found by Fenwick and Paulay [7] to reduce aggregate interlock by more than half. It can only be concluded, therefore, that, in the absence of transverse reinforcement, the main contributor to the shear resistance of an RC beam at its ultimate limit state is the compressive zone, with the region of the beam below the neutral axis making an insignificant, if any, contribution.

As for the concepts discussed so far, the test results are also in conflict with the truss or strut and tie concepts. A large portion of the shear span of beams C and D cannot behave as the models imply, since neither the absence of transverse reinforcement allows the formation of ties nor the presence of a wide inclined crack permits the formation of a strut. And yet, the beams sustained loads significantly larger than those widely expected. Such behaviour indicates that, in contrast with widely held views, truss or strut and tie behaviour is not a necessary condition for the beams to attain their flexural capacity once their "shear capacity" is exceeded.

The validity of the conclusions drawn from the results discussed above is supported by the results (see Fig. 2b) obtained in a more recent experimental work [8] which involved the testing of the RC beams also shown in Fig. 2b. The figures indicate not only that restricting the transverse reinforcement within the compressive zone does not reduce the load-carrying capacity of the beams, but also that designing such reinforcement so as to provide a more effective confinement to the compressive zone improves significantly both strength and ductility. It would appear, therefore, that, in contrast with current views, it is the compressive zone, and not the portion of a structural concrete member outside this zone, that provides shear resistance to the member.

4. MECHANISMS OF SHEAR RESISTANCE AND FAILURE

The underlying causes of shear resistance of the compressive zone have been investigated by testing RC T-beams with a web width significantly smaller than that considered, in compliance with current thinking, to provide adequate shear resistance [9]. Design details of a typical beam with a 2.6 m span tested under six-point loading are shown in Fig. 3 which also shows a typical mode of failure. The tests indicated that the load-carrying capacity of the beams was up to three times higher than that predicted on the basis of the currently accepted concepts. It was also found that failure usually occurred in regions not regarded by current Code provisions as the most critical. As the web width of these beams was inadequate to provide shear resistance, the above results support the view that the region of the beam above the neutral axis - the flange in the present case - is the main, if not the sole, contributor to shear resistance.



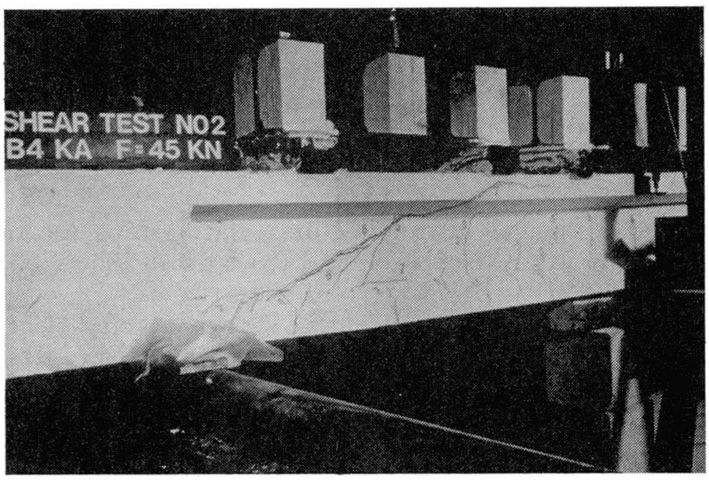


Fig. 3 RC T-beams under six-point loading. Design details and mode of failure [6].

It is also interesting to note in Fig. 3 that the inclined crack, which eventually caused failure, penetrated very deeply into the compressive zone. In fact, it locally reduced the depth of the neutral axis to less than 5% of the beam depth. In view of such a small depth of the compressive zone, it may be argued that concrete is unlikely to be able to sustain the high tensile stresses caused by the presence of the shear force. Such an argument is usually based on the erroneous assumption that concrete behaviour within the compressive zone of a beam at its ultimate limit state is realistically described by using uniaxial stress-strain characteristics. This assumption is in conflict with recent experimental information which has demonstrated quite conclusively that the stress conditions within the compressive zone of an RC beam at its ultimate limit state are triaxial [6,10]; in fact, concrete in the region of a section through the tip of a deep flexural or inclined crack is subjected to a wholly compressive state of stress which represents the restraining effect of the adjacent concrete [10]. It is considered that a part of the vertical and horizontal components of this compressive state of stress counteracts the tensile stresses developing in the presence of the shear force. Hence, in spite of the presence of such a force, the state of stress remains compressive and this causes a significant enhancement of the local strength; a schematic representation of the mechanism providing shear resistance is shown in Fig. 4. However, eventually the shear force increases beyond a critical level and results in the development of tensile stresses sufficiently large to eliminate the restraining effect of the adjacent concrete thus creating a compression/tension stress field which reduces abruptly the local strength and causes failure.

5. IMPLEMENTATION IN DESIGN

A recent attempt to summarize the experimental information discussed in the preceding sections and present it in a unified and rational form has led to the formulation of the concept of the compressive force path [6]. On the basis of this concept, the load-carrying capacity of a structural concrete member is associated with the strength of concrete in the region of paths along which compressive forces are transmitted to the supports. The path of the compressive force may be visualized as a "flow" of compressive stresses with varying section perpendicular to the path direction and with the compressive force representing the stress resultant at each section (see Fig. 5). Failure has been shown to relate with the presence of tensile stresses in the region of the path and such stresses may develop due to a number of causes, the main ones being associated with changes in the path direction, the varying intensity of the compressive stress field along the path, bond failure at the level of the tension reinforcement between two consecutive flexural or inclined cracks, etc.

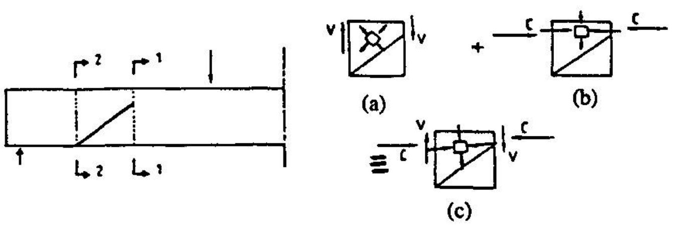


Fig. 4 Mechanism providing shear resistance.

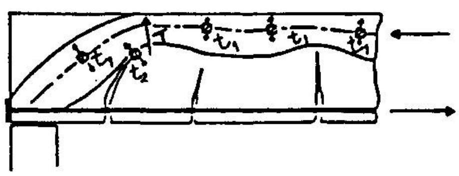
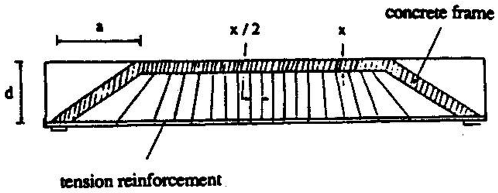


Fig. 5 Compressive force path.

The above concept has been implemented in design by modelling an RC beam as a frame with inclined legs tied by the tension reinforcement (see Fig. 6) with the frame providing a simplified representation of the compressive force path. In compliance with the proposed concept, failure of the model should occur due to failure of either the horizontal or inclined members of the frame or the joint of these members. A full description of the model together with design examples and experimental verification forms the subject of other publications [eg. 11] where it is shown that the resulting design solutions are not only more economical but also safer than those obtained by using the methods recommended by current Codes of practice. A typical example of the application of the above model in design is given in Fig. 1a which shows the design details of a simply supported beam subjected to four-point loading together with the load-deflection curve established by experiment. The Figure also includes the values predicted for load-carrying capacity by current Codes as well as that predicted by the proposed model and it is interesting to note that while the beam strength is closely predicted by the proposed model, it is between approximately 5 and 20 times larger than the Code predicted values. It is also important to note that the above model can form the basis for the design of more complex skeletal structural forms such as, for example, continuous beams, frames, etc. In such cases, the model shown in Fig. 6 represents an element of a skeletal structural form between two consecutive points of zero bending moment, as indicated in Fig. 7, with the transverse reinforcement at the point of zero moment being designed so as to represent an internal support forming between two consecutive beam elements.



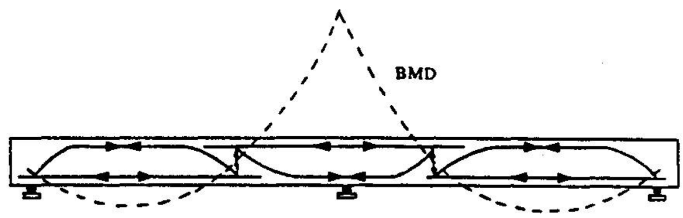


Fig. 6 Model for simply-supported beams.

Fig. 7 Model for a continuous beam.

6. CONCLUSIONS

1. The concepts underlying shear design methods are found to be incompatible with the observed behaviour of RC beams. Shear capacity is shown to be provided by the compressive zone and not, as widely believed, the portion of the beam below the neutral axis.

2. Shear resistance is associated with the development of a triaxial compressive state of stress in the region of the tip of deep inclined cracks and failure eventually occurs due to the development of transverse tensile tensile stresses within the compressive zone.

3. Modelling an RC beam as a frame with inclined legs tied by the tension reinforcement is shown to lead to design solutions which are both safer and significantly more economical that those currently obtained. Such a model may be considered to represent the portion forming between consecutive points of inflection of any skeletal structural concrete configuration.

7. REFERENCES

1. American Concrete Institute. Building Code Requirements for Reinforced Concrete, ACI 318-83 (1983).

2. British Standards Institution. Code of Practice for Design and Construction, BS8110, 1 (1985).

3. Canadian Standards Association. Design of Concrete Structures for Buildings, CAN3-A23.3-M84 (1984).

4. CEB-FIP Model Code for Concrete Structures. Bulletin d' Information 124-125 (1978).

5. Schlaich J. and Schafer K. Konstruieren im Stahlbeton, Beton-Kalender 1984, Wilhem Ernst und Sohn, Berlin, 87-1004.

6. Kotsovos, M. D. Compressive force path: Basis for ultimate limit state reinforced concrete design. ACI Journal, 85 (1988), 68-75.

7. Fenwick, R. C. and Paulay, T. Mechanisms of shear resistance of concrete beams. Journal of the Structural Division, ASCE, 94 (1968), 2325-2350.

8. Kuttab A. Beam Tests. Presented at meeting of CEB Task Group 24 held in Dubrovnik (1988).

9. Kotsovos, M. D. , Bobrowski, J., and Eibl, J. Behaviour of RC T-beams in shear. The Structural Engineer, 65B (1987), 1-10.

10. Kotsovos, M. D. Consideration of Triaxial Stress Conditions in Design: A Necessity. ACI Journal, 84 (1987), 266-273.

11. Kotsovos, M. D. and Lefas, I. D. Behaviour of reinforced concrete beams designed in compliance with the compressive force path. ACI Structural Journal, 87 (1990), 127-139.

12. Maier J. and Thurlimann B. (1985) Bruchversuche an Stahlbetonscheiben. Bericht No. 8003-1, Institut für Baustatik und Konstruktion, ETH Zurich.