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TOWARDS A RATIONAL DESIGN OF DEEP BEAMS

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SYNOPSIS

Reinforced concrete (RC) deep beams have useful applications in tall buildings, foundations and offshore structures. However, their design is not covered adequately by various codes of practice. Whereas the British Code BS 8110 explicitly states that for the design of deep beams reference should be made to specialist literature, the American Code ACI 318 permits the use of methods that satisfy equilibrium and strength requirements as an alternative to the provisions summarized in it. Recently, some works have been presented where it has been suggested that modelling a deep beam as a tied frame with inclined legs yields realistic predictions of load carrying capacities and, therefore, may form a suitable basis for a rational design procedure. The concepts that form the core of the above mentioned design approach indicate that a deep beam will withstand the action of an applied load if the resulting internal actions can be safely sustained by the members of the proposed model.

The present paper describes the design methodology in brief and attempts to verify the basic tenets of the method by assessing the load carrying capacity of a very large number of deep beams, the experimental behaviours of which are available in the published literature. During the course of assessment, both ACI 318 and the proposed design methodology have been employed. Attempts have been made to correlate predicted load carrying capacities with their experimental counterparts. Very good correlation has been obtained between the experimental values of failure loads with the failure loads predicted by the method advocated in the present paper. The apparent simplicity of the new design methodology, as well as its good performance in predicting failure loads, warrant its use for arriving at an all encompassing design rationale of deep beams.

INTRODUCTION

Deep beam behaviour is an important consideration in the design of pile cap, transfer girder, foundation walls, walls of rectangular tanks and bins, floor diaphragms, shear walls, as well as folded plate roof structures. The behaviour of deep beams is significantly different from that of slender beams of normal proportions. Deep beams require special consideration in analysis, design and detailing of reinforcement. Deep beams are those members which have depth (d) quite large in comparison to the span (L), while the thickness in the perpendicular direction is múch smaller. The transition from ordinary-beam behaviour to deep-beam behaviour is imprecise. Again, although the span-to-depth ratio (L/d) is the most frequently quoted parameter governing deep-beam behaviour, the shear span-to-depth ratio (a/d) is, perhaps, more important. In the present study, beams having a/d up to 1.5 has been considered as deep beam, since quite a large number of beams of this category have been reported as deep beams in the literature. Present design rules of deep beams are usually based on the provisions of ACI 318-89 [1], CIRIA Guide 2 [2], CSA A23.3-M84 [3] and other well recognised codes. Again, while the British Code BS 8110 [4] explicitly states that for the design of deep beams reference should be made to specialist literature, the American Code ACI 318 permits the use of methods that satisfy equilibrium and strength requirements as an alternative to the provisions summarized in it. In general, the presently available methods do not usually provide an accurate estimate of the shear strength of deep beams, rather they generally predict very conservative strength. It is worth mentioning here that some of the available methods are quite,difficult to apply in the design of deep beams.

It appears that although a good amount of effort and time have been spent so far by various researchers in an effort to investigate and understand the behaviour of deep beams, these studies have not lead to unified conclusions [5]. Usually, the investigators have tested a set of deep beams by varying one or more parameters and, based on these test results, they have proposed different empirical formulae and design rationale. Most of these methods fail to perform satisfactorily when tested against a set of new test data which were not previously used in calibrating/tuning the formulae. Serious conflicts between the code provisions and research findings have also been observed [5]. Kotsovos [6] has claimed that the current code for deep beams are the modified forms of the design methods of long beams. He has shown that the current methods for the design of deep beams are unsatisfactory not only because of the lack of a sound underlying theory, but also because they include most of the unsatisfactory elements of the methods currently used for the design of long beams. A model has also been proposed by Kotsovos [6], for the design of deep beams (with a/d up to 1.0), in accordance with the compressive force path (CFP) concept of Kotsovos [7]. Kotsovos and Lefas [8] deals with the design method of beams having a/d greater than 1.0. The present paper compares the experimental results of a large number of deep beams reported in Kong, et al. [9], Mansur, et al. [10], Manuel, et al. [11], Mau and Hsu [12,13], Paiva and Siess [14], Rogowsky and Macgregor [15,16] and Subedy, et al. [17] with the predictions of ACI 318-89 [1] and the CFP model of Kotsovos [6,7] and Kotsovos and Lefas [8].

COMPARISON OF PREDICTED LOAD CARRYING CAPACITY OF RC DEEP BEAMS WITH EXPERIMENTAL VALUES REPORTED IN [9-17]

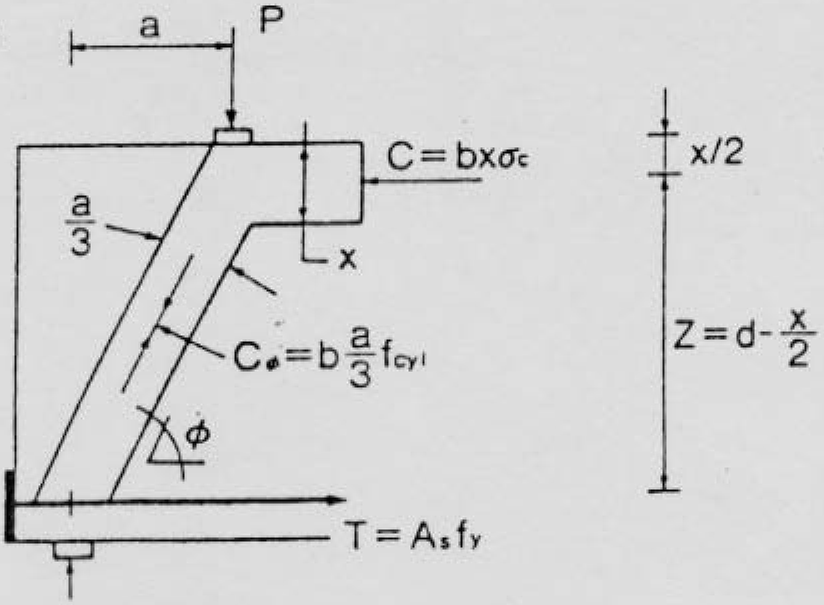
The test results of a total of 141 deep beams are available in References [9-17]. Out of these deep beams, 84 fall in the range $a/d \leq 1.0$, while the other 57 deep beams fall in the range $1.0 < a/d \leq 1.5$.

ACI 318-89 method Calculations of shear strength of simply supported deep beams are carried out for critical sections as defined in the code. For uniformly distributed loading, the critical section is taken as 15 percent of the clear span from the face of the support; for a concentrated load, it is taken as half way between the load and the face of the support. The shear reinforcement required at the critical section is used throughout the span. Details of the method is available in ACI 318-89 [1] and various text books.

CFP method A detailed description of the CFP method as applicable to structural concrete members is available elsewhere in Kotsovos [6,7], Kotsovos and Lefas [8] and Seraj et al. [18-19]. A very brief description of the method pertaining to the design of members having a/d up to 1.5 is describes here.

For $a/d \leq 1.0$, the CFP model essentially represents a deep beam and brittle failure is associated with failure of the inclined leg. Kotsovos [6] suggests that the most effective way to prevent such failure is by adjusting the cross-sectional area of the beam so as to satisfy condition (c) in Figure 1, and providing nominal reinforcement such as that specified in current design practice. Designing web reinforcement in compliance with current design methods should not be relied upon to safeguard against brittle failure since presence of such reinforcement has an insignificant effect on the load-carrying capacity. On the other hand, the provision of nominal reinforcement is essential since it practically eliminates the possibility of instability caused by unforeseen out-of-plane actions.

For $1.0 < a/d < 2$, failure of the CFP can be prevented by increasing the section moment resistance to the level of the applied bending moment through the provision of web reinforcement in the form of stirrups uniformly distributed throughout the portion of the model between the support and the joint of the frame members, as described in Figure 2. Such reinforcement should be designed such that, at yield, it would be capable of sustaining a total tensile



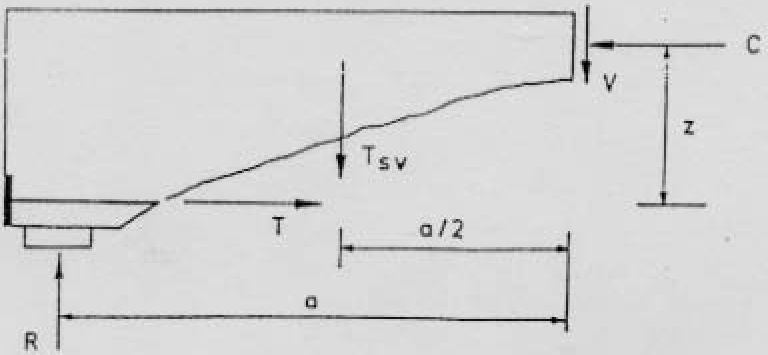
(a) Moment equilibrium $C \cdot z = P \cdot a$ yields x

(b) Horizontal force equilibrium $T = C$ yields A_s

(c) Check whether a/3 satisfies vertical force equilibrium $C\phi \cdot \sin\phi = P$ if not, adjust b and repeat.

Note: $\sigma_c = 0.8\ f_{cyl} = 0.64\ f_{cu}$

Figure 1: Proposed Method for Designing a RC Deep Beam ($a/d \leq 1.0$) [6]



$$R\,a - T_{sv}\,(a/2) = T\,z$$

i.e. $M_f - T_{sv}\,(a/2) = M_c \quad \Rightarrow T_{sv} = 2(M_f - M_c)/a$

Note: M_f is the flexural capacity (Nmm)

M_c is the moment corresponding to failure load [8]

Figure 2: Proposed Method for Designing a RC Beam ($1.0 < a/d \leq 1.5$) [8]

force $T_{SV} = A_{SV} f_{yv}$. The beams with a/d between 1.0 and 1.5 fall under this category.

Sultan's modified method Sultan [5] opined, after conducting some preliminary studies, that the width of the compressive strut should increase with decreasing values of a/d below 1.0. Sultan [5], after noticing that CFP method underestimates the capacity of the member for very small values of a/d, proposed that for a/d $\leq$ 1.0, the width of the compressive strut may be taken as $\sqrt{ad}/2.7$ instead of a/3. This effectively increases the width of the compressive strut as a/d decreases.

Presentation of results Figure 3 compares experimental strength of 84 deep beams (a/d $\leq$ 1.0) with their ACI and CFP counterparts. Strength predicted by Sultan's modified approach (M) has also been shown in the figure. Similarly, in Figure 4, experimental strength of 57 deep beams (1.0 < a/d < 1.5) has been compared with ACI and CFP predictions. It is clear that while ACI code grossly underestimated the strength, the performance of CFP was satisfactory. Statistical calculations have revealed that for deep beams with a/d $\leq$ 1.0, the mean values of CFP/Experiment, ACI/Experiment and M/Experiment were 0.8838, 0.5789 and 1.1879, respectively. Similarly, for beams with 1.0 < a/d < 1.5, the mean values of CFP/Experiment and ACI/Experiment were 1.0388 and 0.7144, respectively.

CONCLUSIONS

The present-day design methods are not capable of addressing the design of deep beams satisfactorily. The compressive force path model, however, could predict the failure loads with sufficient accuracy. The apparent good performance of the method, coupled with its simplicity in comparison to other procedures, encourages further investigations pertaining to the suitability of the CFP method in practical design purposes. Deep beams designed to this method may be tested in the laboratory to further verify the tenets of the methodology, although the good correlation between the predicted and experimental values of the very large number of deep beams analysed here points to the validity of the concepts that form the basis of the design rationale advocated in the present paper.

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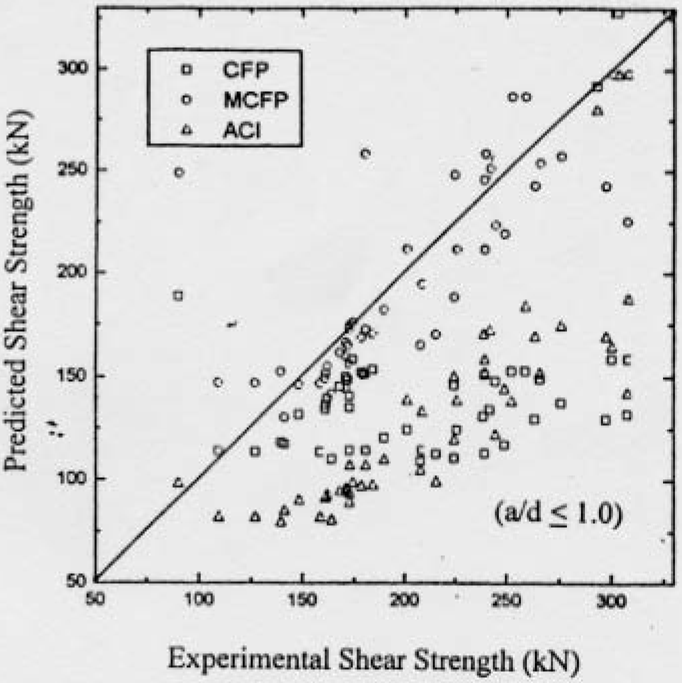
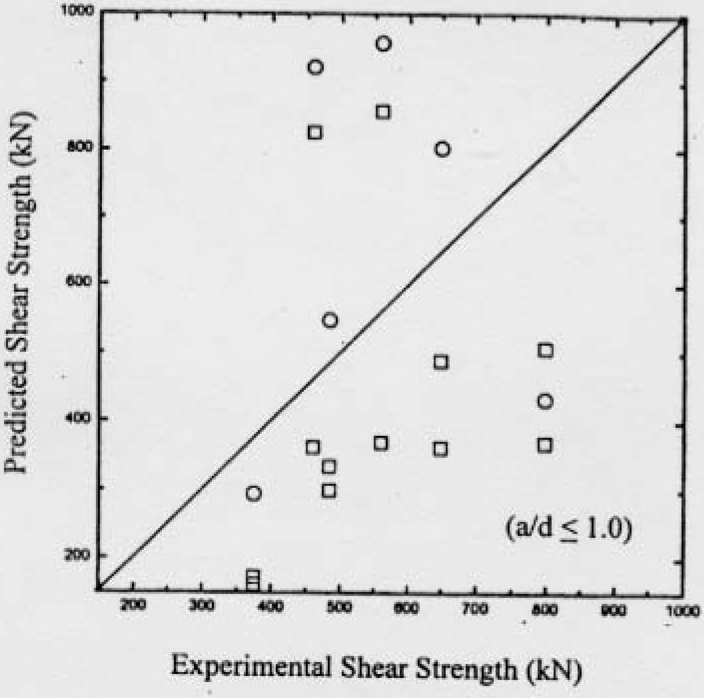
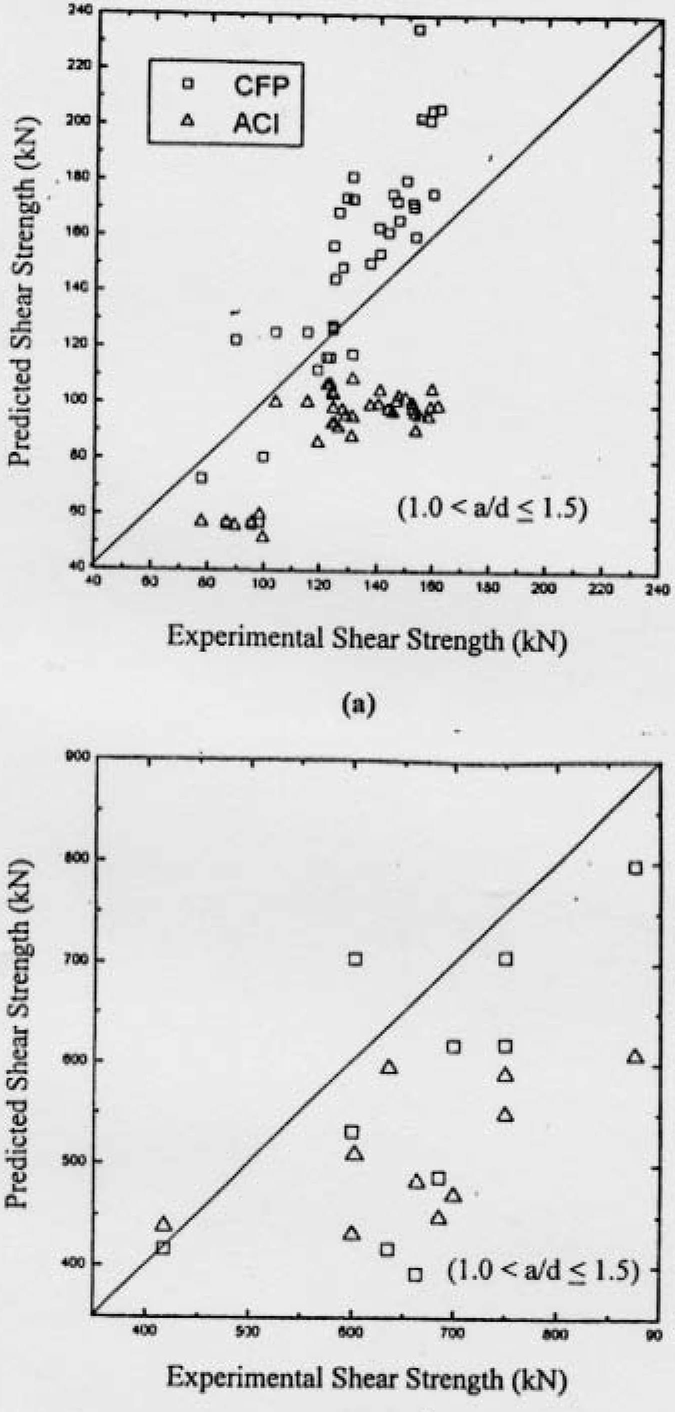


(a)



(b)

Figure 3: Comparison of Predicted Strength with Experimental Strength of (a) Small Capacity and (b) Large Capacity Deep Beams having a/d ≤ 1.0



(a)

(b)

Figure 4: Comparison of Predicted Strength with Experimental Strength of (a) Small Capacity and (b) Large Capacity Deep Beams having 1.0 < a/d ≤ 1.5

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