Mechanisms of 'shear' failure*

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The paper by Dr Kotsovos is an interesting one as it tries to shed new light on the physical nature of shear failures. However, I would seriously question the generality of many of the phenomena described and would doubt that such rather vague descriptions of behaviour could replace the models presently used in design and research. I discuss a number of specific points.

Dr Kotsovos's type II behaviour is what is normally regarded as diagonal tension failure arising from flexure–shear cracking. The current models of teeth of concrete divided by flexural cracks and acted on by bond, aggregate interlock and dowel forces, e.g. that of reference 1 below, seem to me to be adequate descriptions of the phenomena involved. If account is taken of the shear transferred across flexural cracks, this together with the vertical tension from cantilever action must be expected to produce the observed inclined cracking. There would seem to be no general validity to the view that diagonal cracking develops from the outermost flexural crack. Figure I shows two examples of behaviour quite different from the Stuttgart shear tests[2].

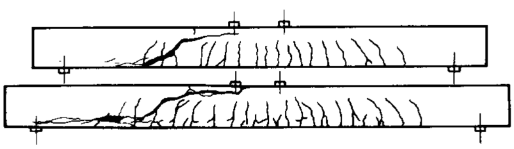


Figure I: Stuttgart shear tests[2]. Failures in beams 7/1 and 8/1.

Type III behaviour is equivalent to resistance after shear cracking arising from arch or strut and tie action and ending in shear–compression failure. The final crushing of the compression zone can occur within the shear span just as well as in a zone of pure flexure.

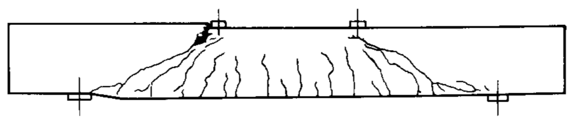
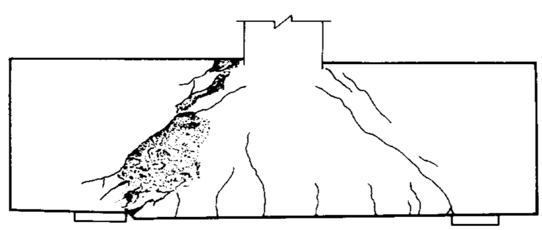
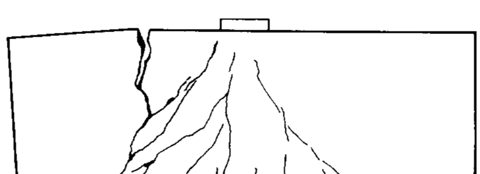


Figure II: Failure of Placas[3] beams R4 (a/d = 2·24).

Figure II is intended to indicate the path of the compressive force through the shear span of the beam without distinguishing between plain (without stirrups) and reinforced (with stirrups) concrete. An inclined path in the region of the load point will result in the 'wedge-like' action that should cause failure of the compressive zone of the flexure span even before the flexural capacity of the beam is attained. The validity of this concept is supported by recently obtained experimental evidence which indicates that, in contrast with a beam with stirrups throughout its span, a similar beam with stirrups within the shear span only fails indeed as described above (Figure VI)[5].



(a) Imperial College J12 (a/d = 1·03)



(b) Al Najjim A4 (a/d = 0·84)

Figure III: Failures of short shear spans.

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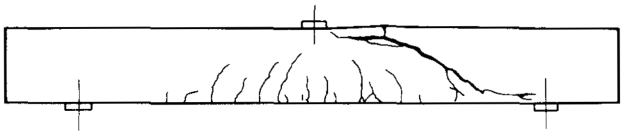
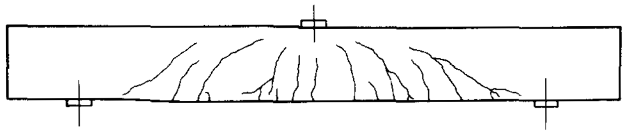
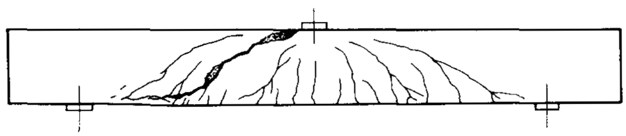


(a) Beam R7 (without stirrups) at failure at 112 kN



(b) Beam R8 (with stirrups) at 120 kN



(c) Beam R8 at failure at 162 kN

Figure IV: Cracking of otherwise similar beams with and without stirrups.

Shear reinforcement does not normally prevent any diagonal cracking, or even much modify the load at which inclined cracks are formed. This can be seen from the example (d) in Figure IV.

If a stable structure is established after shear cracking, its general form seems inevitably to be practically the opposite of that shown in Figure 11 of the paper. In the absence of stirrups, the only available resistance is that afforded by the inclination of the main compression. The force path must thus run straight from the load to the support, i.e. along the line labelled 'calculated shear reinforcement'. On the other hand, if significant stirrups are present, a truss-like action is established and the line of the main thrust is kept higher and approximates to that labelled 'no shear reinforcement'.

Reply by the author

I wish to thank Dr Regan for his interest in the paper and contribution. In reply, I would like to make the following comments.

TYPE II BEHAVIOUR

Dr Regan considers that the current models of the concrete 'teeth' acted upon by bond, aggregate interlock and dowel forces provide an adequate description of the 'shear' phenomena. However, the mechanisms of aggregate interlock and dowel action are incompatible with the observed behaviour of concrete at the material level. Cracking has been found always to propagate in the direction of the maximum principal compressive stress (or orthogonally to the direction of the maximum principal tensile stress) and to open in the orthogonal direction[6,7]. Furthermore, analytical investigations of the cracking processes of reinforced concrete beams under two-point loading have indicated that a realistic description of the beam behaviour can be obtained on the basis of the fundamental material properties and ignoring both aggregate interlock and dowel action[8]. It appears to me that, in most cases, experimental research carried out to date has concentrated on proving that significant forces can be transferred through aggregate interlock and dowel action, rather than on demonstrating that aggregate interlock and dowel action represent mechanisms of load transfer characterizing reinforced concrete structural members.

I have considered as general the view that diagonal cracking initiates near the tip of the flexural crack closest to the support since this is a view expressed in textbooks, e.g. reference 9. The failures in the Stuttgart shear tests indicate that, although diagonal cracking may not always initiate near the tip of the outermost flexural crack, it does certainly initiate near the tip of a flexural crack closest to the support rather than the load point (see Figure I of Dr Regan's contribution). Such behaviour may characterize the transition between types of behaviour I and II (see Figure 3 of the paper) since it occurred for $a_v/d > 5$. Nevertheless, it is by no means incompatible with the causes of 'shear' failure described in the paper.

TYPE III BEHAVIOUR

A recent experimental programme[10] has confirmed that this type of behaviour is indeed characterized by failure of the compressive zone of the flexure span in the region of the load point (see Figure V). However, for $2{\cdot}0 < a/d < 2{\cdot}5$, bond failure or the presence of compression reinforcement may lead to the failure mode exhibited by beam R4 (see Figure II of Dr Regan's contribution). These effects are currently under investigation.

TYPE IV BEHAVIOUR

There must be a misunderstanding regarding this type of behaviour since the beams in Figure III (Dr Regan's contribution) do not have a flexure span (i.e. span with $V = 0$). For beams with such a span, collapse occurs owing to failure of the compressive zone of this span in the region of the load point. In the

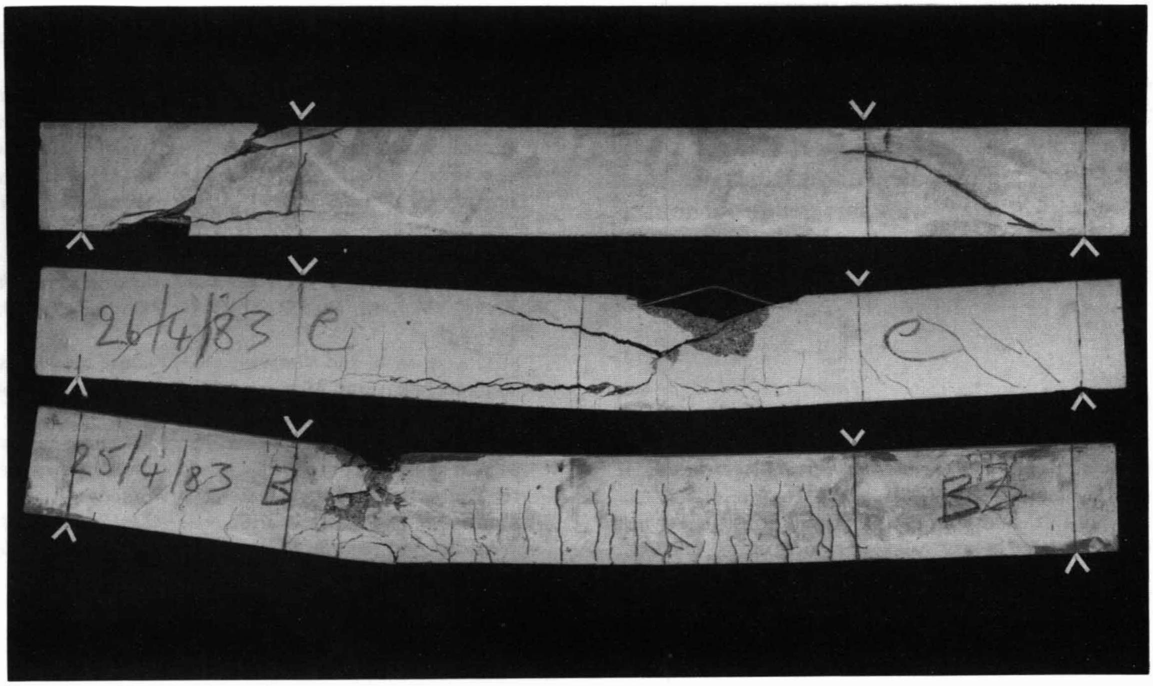


Figure V: Modes of failure exhibited by beams without stirrups with $a_v/d < 2{\cdot}0$.

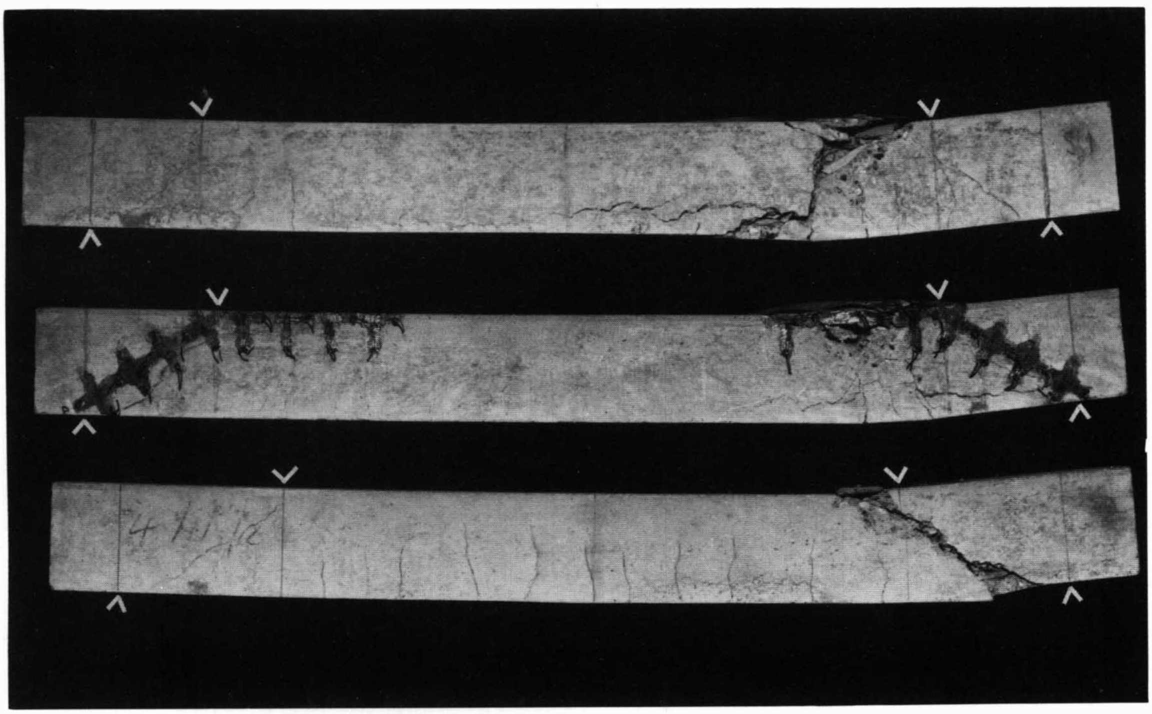


Figure VI: Modes of failure exhibited by beams with stirrups arranged as follows (from top to bottom): no stirrups, with stirrups within shear span, stirrups through beam length.

absence of a flexure span, a beam should fail as indicated in Figure III.

EFFECT OF SHEAR REINFORCEMENT

The discussion of the effect of shear reinforcement upon the mode of failure, presented in the paper, refers to the branch of the diagonal crack that travels through the compressive zone towards the support and leads to collapse of the beam (Figure 10 of the paper).

Figure II is intended to indicate the path of the compressive force through the shear span of the beam without distinguishing between plain (without stirrups) and reinforced (with stirrups) concrete. An inclined path in the region of the load point will result in the 'wedge-like' action that should cause failure of the compressive zone of the flexure span even before the flexural capacity of the beam is attained. The validity of this concept is supported by recently obtained experimental evidence which indicates that, in contrast with a beam with stirrups throughout its span, a similar beam with stirrups within the shear span only fails indeed as described above (Figure VI)[5].

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