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Interpretation of Modified Shear Failure in RC Beams

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Abstract:
Present study describes an investigation into the causes of shear failure of reinforced concrete beams subjected to two point loading with shear span/depth ratio greater than 2.5. In this investigation tests are carried out on four reinforced concrete beams labelled as B1, B2, B3 and B4 are identical in geometry, flexural reinforcement, material properties and test details. The only variable is shear stirrups spacing along the member length. Strength and performance of beams with various arrangements of stirrups are verified. An experimental study of beams with various arrangements of shear stirrups has indicated that the predicted behaviour is incompatible with the concept of shear capacity at critical sections that forms the basis of current shear design procedures. The results obtained support the view that shear failure is associated with the development of tensile stresses within the compressive zones of the beams.

Key words: *shear stirrups, shear capacity, finite element, reinforcement.*

I. Introduction:

The main aim of the current investigation is to study the causes of shear failure of reinforced concrete beams subjected to two point loading with shear span/depth ratio greater than 2.5.It also characterises the magnitude of the ductility in terms of deflections and crack widths between the beams for the two legged conventional shear reinforcement Shear design procedures are generally considered to be unsatisfactory inspite of the considerable efforts that are continuously made to revise them. These concepts mainly stem from the widely held views that reinforce concrete beams without stirrups fail in shear when the shear capacity of critical section is exceeded. Thus the objective of all current design procedures is to realistically assess the amount of shear reinforcement required to carry that portion of the shear force that cannot be sustained by concrete alone.

Michael D.Kotsovos (1986) indicated by finite element analysis and verified by experiment that, for beams under two point loading with shear span/depth ratio ranging between 2.0 and 2.5. The causes of shear failure cannot be explained in terms of the concept of shear capacity of critical sections. This is because on the basis of this concept, beams with the same geometry and tension reinforcement, but without stirrups within the shear span, should have the same load-carrying capacity irrespective of the presence of stirrups outside this span. And yet it was found that the load sustained by beams with stirrups within the middle, and not the shear span was significantly larger than that of beams without any stirrups. Furthermore, it was found that the load sustained by the beam without shear reinforcement was essentially equal to that of beams with stirrups within the shear span. The causes of shear failure are associated with the stress conditions in the region of the path along which the compressive force is transmitted to the supports and with the stress conditions in the region of the beam below the neutral axis, as is widely believed. The present work is concerned with an attempt to verify the validity of the previously described view by means of experimental investigations. In the following, the research work into the causes of shear failure is complimented by considering beams with shear span-to-depth ratios larger than 2.5.

II. Research Significance:

The work described in this paper forms part of a research program investigating the various shear modes of failure exhibited by reinforced concrete structural members under two point load. It is considered that these modes of failure are associated with multi-axial stresses conditions that exist in the region of the paths along which the compressive forces are transmitted to the supports, rather than with the shear capacity of critical cross-sections.

III. Experimental Research:

Shear tests were carried out to characterise the shear behaviour relative to variation in stirrup spacing of reinforced concrete beams. The experimental programme involved tests on four identical shear critical reinforced concrete beams. The beams are designated as B1, B2, B3, and B4, and the details are illustrated in Fig 1.To address the previously stated research objective in the four beams, the stirrup legs were placed and explained in Table 1. Shear reinforcement configuration in the test specimens B1, B2, B3 and B4 are shown in

Fig 1. All beams were 150mm wide, 300mm deep, and 2400mm long. The amount of flexural reinforcement in the beams was same. Shear span to effective depth ratio also same. During testing, the beams carried two concentrated loads act at a distance of 400mm on either side from the mid span. The properties of test specimens are presented in Table 2.

Table 1:- Arrangement of shear reinforcement in beams

Beam ID	Description
B1	No shear stirrups.
B2	Shear stirrups provided throughout the span.
B3	Stirrups provided within the region of the shear span between the cross section at the support and that is at a distance of 2d (534mm) from the support of beam.
B4	Stirrups provided throughout the span except in the regions reinforced with stirrups in beam B3.

Figure 1: Typical longitudinal and cross sectional configuration of specimens B1, B2, B3 and B4

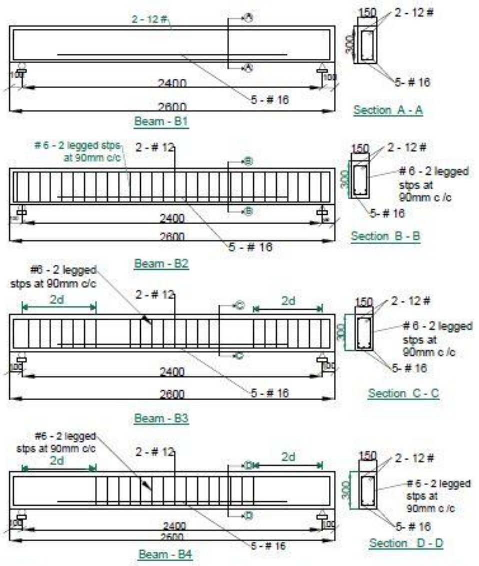

Fig. 1Typical Longitudinal and cross sectional configurations of specimens B1, B2, B3 and B4

IV. Material properties:

In the concrete prepared for the production of test specimens,cement used was 53 grade ordinary Portland cement, and the fine aggregate was river sand confirming to zone II as per IS: 383(BIS, 1970); The coarse aggregate was locally available crushed granite stone sieved to 20 mm maximum size, also satisfying the requirements of IS: 383 (BIS, 1970); 20 mm and 10mm aggregate sizes were used. The mix proportion by weight of cement, sand and coarse aggregate was, respectively, 1.0: 1.74: 3.51, with water to cement ratio of 0.5 by weight. All flexural reinforcing steel used was high-yield-strength bars. Specimen moulds for casting of beams were made of brick masonry on the laboratory floor and plastered smooth with cement mortar. The concrete materials were weigh-batched and mixing was done in a concrete mixer. The concrete was placed in the moulds and needle vibrated. From the same mix, control cubes and cylinders were cast. Curing of specimens started after 24 hours from casting and continued for 28 days. As the curing ended, the specimens were prepared for testing.

Table 2 :- Properties of test specimens

Specimen label	Width (mm)	Overall Depth (mm)	Effective Depth (mm)	Effective Span (mm)	Shear Span/ effective depth	Flexural reinforcement		Shear reinforcement spacing	Cube compressive strength at 28 days (N/mm^2)	Split tensile strength at 28 days (N/mm^2)
						Bottom	Top			
B1	150	300	267	2400	3	5 - 16 mm dia	2-12 mm dia	No shear reinforcement	31.66	2.67
B2	150	300	267	2400	3	5 - 16 mm dia	2 -12 mm dia	6mm dia 2 Legged vertical stirrups @ 90 mm c/c throughout the total length of beam.	33.52	2.8
B3	150	300	267	2400	3	5 - 16 mm dia	2 -12 mm dia	6mm dia 2 Legged vertical stirrups @ 90 mm c/c provided up to 2d from support and between two point loads.	33.52	2.8
B4	150	300	267	2400	3	5 - 16 mm dia	2 -12 mm dia	6mm dia 2 Legged vertical stirrups @90mm c/c provided total length of beam except at 2d from the support.	33.52	2.8

V. Testing procedure:

All the tests were conducted in a steel loading frame. The beams were tested on a simply supported span of 2400mm with a two concentrated loads act at a distance of 400mm on either sides of the beam from the mid span. The load was applied by hydraulic jack of 1000kN capacity. The applied force was controlled through manual operation. Instrumentation for the test specimen was designed to obtain the measurement of transverse load and to capture the load-deflection response and crack development. To address the previously stated research objective, strength and serviceability data were collected for each test. A dial gauge was employed for recording mid-span deflection. To measure the deflection, a dial gauge of 20mm run was utilized at mid span having least count of 0.01mm. The crack widths are measured using hand micro scope with least count of 0.02mm. A schematic diagram of the load test set-up for loading the beams is provided in Fig 2. At each load stage, magnitude of the load stage, magnitude of the load on the test specimen, central transverse deflection of the beam and maximum crack width were recorded. The cracks were marked on the beam surfaces.

The principle test results are summarised in Table 3. At the termination of test, the beams were photographed to depict crack pattern and failure mode. For all the beams, the measured transverse mid span deflections is plotted against the applied loads in Fig 3. Fig.4 illustrates the moment- crack width relationships for the tested specimens. The photographs for the tested beams with crack patterns after failure are presented in Fig 5.

VI. Presentation of test results:

In beam B1, the initial crack originated was shear at the support of the side face at 44kN-m, which was 73.3% of ultimate moment. With load increased, diagonal cracks formed in the shear span on either sides of the load on the side faces. The shear failure occurred suddenly at moment 60kN-m. Increases in load extended the diagonal cracks to the top face and the crack width widened. With slight shear compression distresses on the top face.In beam B2, stirrups provided throughout length of the span, initial crack is appeared at the near to support of the side face at 40kN-m, which was 48% of ultimate moment. As the load increased, several diagonal cracks formed in the shear span on either side of the load on the side faces, and extended towards the top face. Ultimate shear force failure occurred at moment 84kN-m.In beam B3, initial crack is appeared at the support of the side face at 48kN-m, which was71% of ultimate moment. As the load increased additional diagonal cracks formed and those already formed extended towards the top face, the crack widths widened. Ultimate shear failure occurred at 68kN-m.The beam B4, stirrups provided throughout length of the span and except at 2d from the support, initial crack is appeared at the near to support of the side face at 40kN-m, which was 45% of ultimate moment. As the load increase, several diagonal cracks formed in the shear span on either side of the load on the side faces, and extended towards the top face. Ultimate shear force failure occurred at moment 88kN-m. Comparision between theoretical and test strengths of beams B1, B2, B3 and B4 are represented in Table- 4.

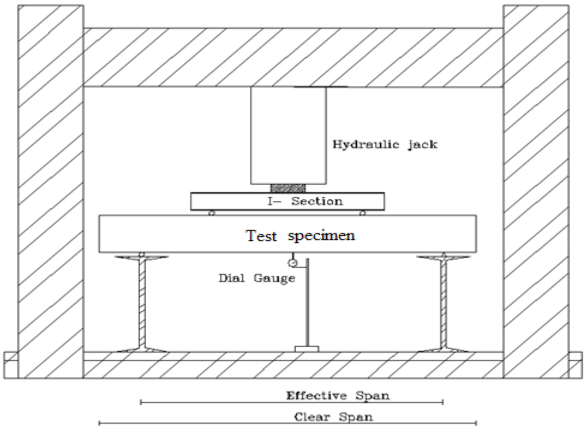

Figure 2: Schematic diagram of the load test set – up for the test specimen

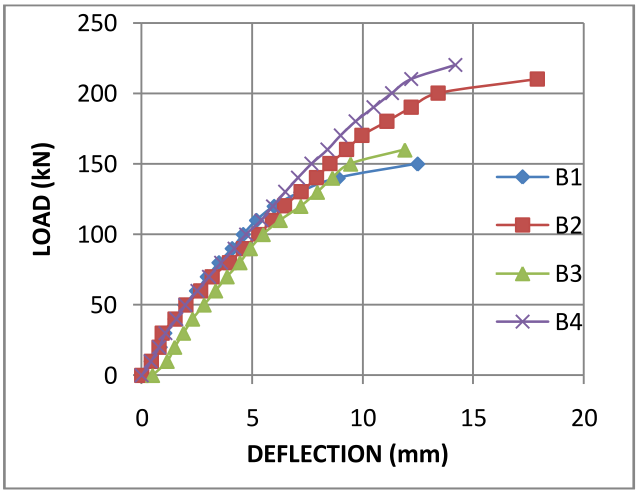

Figure 3: Load plotted against mid-span deflection for beams B1, B2, B3 and B4

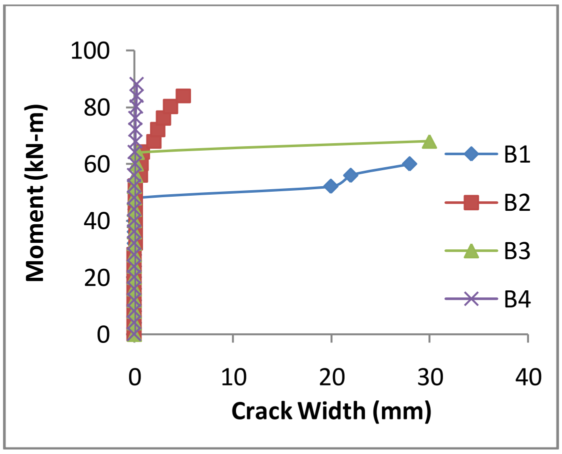

Figure4: Moment and Crack width curve relationships for beams B1, B2, B3, and B4

Table 3:- Principal test results of specimens

Specimen Label	Moment at first crack (kNm)	At Service load					At Ultimate load						
		Moment (kNm)	Shear force (kN)	Shear stress (MPa)	Deflection at mid span (mm)	Crack width (mm)	Load (kN)	Moment (kNm)	Shear force (kN)	Shear stress (MPa)	Deflection at mid span (mm)	Crack width (mm)	Type of failure
B1	44	40	50	1.24	5.3	No crack	150	60	75	1.85	12.5	20	shear
B2	40	40	50	1.24	4.62	No crack	210	84	105	2.5	17.9	5	shear
B3	48	40	50	1.24	4.92	No crack	170	68	85	2.1	11.9	30	shear
B4	40	40	50	1.24	4.73	No crack	220	88	110	2.7	14.2	12.9	shear

Table 4:-Comparison between theoretical and test strengths of beams B1, B2, B3 and B4

Specimen	Shear span to effective depth ratio	f_{ck} (MPa	Theory		Test			$M_{u(test)}/M_{u(theory)}$	$V_{u(test)}/V_{u(theory)}$
			V_u (kN)	M_u (kNm)	V_u (kN)	Shear Stress (MPa)	M_u (kNm)		
B1	3	31.6	75	64.6	75	1.87	60	0.92	1
B2	3	31.6	75	64.6	105	2.6	84	1.3	1.4
B3	3	31.6	75	64.6	85	2.12	68	1.05	1.13
B4	3	31.6	75	64.6	110	2.74	88	1.36	1.46

VII. Discussion of Test Results:

From the concept of shear capacity of a critical section, beams B1, B3, and B4 must have same load-carrying capacity since they have no stirrups either throughout or in large part of their shear span where the shear force is constant. Table 3 indicates that beams B1 and B3 represent nearly the same load carrying capacity. Beam B4 has a load carrying capacity greater than that of beam B1.The load carrying capacity of beam B4 is essentially equal to that of beam B2, which is reinforced with stirrups throughout length of the beam, it reduced amount of inclined cracking within shear span and also good at flexural capacity. The above results cannot explain by shear capacity of critical section. A beam subjected to two-point load with shear span to depth ratio greater than 2.5 is characterised by a path of compressive force consisting of two near-linear portions. Compressive zone is formed at 2d from the support. Placing stirrups within the shear span beyond a distance approximately 2d from the support prevents the occurrence of the near horizontal crack and hence increases the load carrying capacity. Placing stirrups within the region of shear span extending 2d from the support is in effective and hence does not improve load-carrying capacity of beam.

The deformational characteristics of beams B1 and B3 are brittle behaviour in these cases, such brittle behaviour should only characterise beams B1 and B3 which failed before their flexural capacity was attained. Beams B2 and B4 should exhibit ductile behaviour, since they failed first in flexural cracks and then in shear cracks. The loss of load-carrying capacity means the resistance of the shear force through beam action impossible. Kani's hypothesis satisfy that shear failure occurs when the flexural capacity of a concrete cantilever between two consecutive cracks is exceeded. By this case, once concrete suffers complete loss of load carrying capacity in the region of tension reinforcement, the transfer of force from cantilever is un-loaded.

Specimen B1 after testing

Specimen B2 after testing

Specimen B3 after testing

Specimen B4 after testing

Figure 5: Beams B1, B2, B3 and B4 after testing

VIII. Conclusions:

Following conclusions are drawn from present study:

1. The initial cracks occurred in beams B1 and B3 at about 70% and in beams B2 and B4 are 45% of their ultimate loads.
2. B2 and B4 failed at higher load than the other beams B1and B3.
3. B2 and B4 have 30% more load carrying capacity than the companion specimens B1 and B3.
4. The deformational characteristics of the beams B1 and B3 are brittle behaviour in these cases, beams B2 and B4 should exhibit ductile behaviour, since they failed first in flexural cracks and then in shear cracks.
5. The reinforced concrete beams with various arrangements of stirrups subjected to two-point loading with shear span-to-depth ratios greater than 2.5 has indicated that the predicted behaviour is incompatible with the concept of shear capacity of critical sections.
6. The obtained results support the view that shear failure is associated with the development of tensile stresses within the compressive zone and in particular region of compressive zone between the sections including: (a). the load point , and (b). a point lying at a distance of about twice the beam depth from the support.
7. Specimen B-2 implies that the stirrups sustain tensile stresses developing within the compressive zone rather than transform the beam into a truss as widely considered.
8. A possible mechanism for the development of such tensile stresses appears to be associated with the destruction of bond between steel and concrete when bond stresses are critical. The occurrence of bond failure prevents the transfer of force from concrete to steel and thus is in conflict with kani's hypothesis that shear failure occurs when one of the concrete cantilevers forming between two consecutive flexural cracks fails in flexure.

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