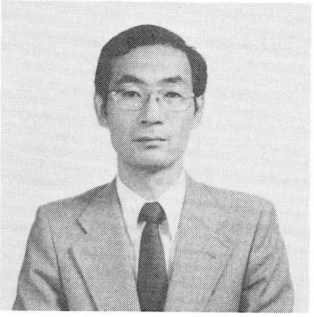
CONCRETE LIBRARY OF JSCE VOL.1, JULY 1983

FUNDAMENTAL STUDY ON SHEAR FAILURE OF REINFORCED CONCRETE BEAMS

(Translation from Proceedings of JSCE, No.279, 1978)



Takeshi HIGAI

SYNOPSIS

Shear behavior of reinforced concrete beams subjected to moving load and fatigue load is studied experimentally. In examining behavior of beam under moving load, special attention is paid to the shear strength in each part of the beam instead of the shear strength of the beam as a whole. Fatigue shear strength is examined based on the test results. The effect of fatigue load on shear strength and mode of failure is also discussed by considering separately the effect of fatigue load on diagonal cracking strength and on the capacity of arch mechanism formed after diagonal cracking. Tentative recommendations to design reinforced concrete for moving load and fatigue load are proposed based on the experimental results. Characteristics of lightweight concrete beams are also discussed to examine the adoptability of the results obtained to ordinary concrete beams, for lightweight concrete is mainly used in the experiment.

T.Higai is an associate professor of the Department of Civil Engineering at Yamanashi University, Kofu, Japan. He recieved his Doctor of Engineering Degree in 1972 from the University of Tokyo. His research interests include problems concerning shear failure of reinforced concrete structures and seismic design of reinforced concrete structures. He is a member of JSCE and JCI.

---

1. Introduction

Many studies concerning the behavior of reinforced concrete beams subjected to combined bending moment and shear force have been carried out until now. Design method for shear force is being reexamined in many countries reflecting the increased knowledge, especially, on the behavior under the ultimate load. But most of the previous experimental researches are concerning to the static loads and there are very few systematic researches concerning the effect of non-static load, moving load or fatigue load for example, on shear behavior of reinforced concrete beams, except the comprehensive study in Japan on the behavior of reinforced concrete columns subjected to the earthquake load. On the other hand, shear failure mechanism has not been fully clarified yet and many design provisions are decided mainly based on the experimental results. It is very important to study the effect of non-static load on the shear behavior before higher allowable shear stress or the reduced amount of shear reinforcement is accepted. Moreover it must be very useful to examine shear failure under the different experimental conditions from that in the previous researches to make more wide base for clarifying shear failure mechanism.

In this paper, results of experimental work which was conducted, from the above view point, to get more information to examine shear behavior of reinforced concrete beams subjected to (simulated) moving load and fatigue load are discussed . That is, based on the results of loading tests of 130 rectanguler and tee sectioned beams subjected to static or fatigue load, shear strength of the beams subjected to moving load is discussed paying special attension to the shear strength in each part of the beam. The effect of fatigue load on shear strength is also discussed by considering separately the effect of fatigue load on diagonal cracking strength and on the capacity of the resisting mechanism alike tied arch which was formed after the development of diagonal cracks. In the experiment, lightweight concrete is mainly used because it is relatively new material and has some different characteristics in strength and stiffness from ordinary concrete, and the use of lightweight concrete is favourable to observe shear behavior under different conditions. Shear behavior of lightweight concrete beams is also discussed to examine the adoptability of results obtained here to the ordinary concrete beams.

2. Shear strength of the beams subjected to simulated moving load

Conventionally, each section of beam is designed for the maximun shear force assuming the location of load which produces maximum shear force to the section is the most critical one. But in almost all of the previous experiments, location of load is fixed and the shear behavior of reinforced concrete beam under moving load has scarcely been examined. In this experiment, specially reinforced concrete beams were used to study the effect of location of load on shear strength of the beam. Effect of impact accompanied by movement of load was not considered here.

2.1 Experimental program

To examine the effect of load position it might be essential to pay attention to the shear strength in each part of the beam instead of the shear strength of the beam as a whole. In the test beams the amount of shear reinforcement was considerablly reduced at specific part (examined part) so that the beam would fail in shear at that part.
Several test beams with examined part at the same location were made and each beam was tested with the load applied at the different location (ratio of shear

span to effective depth a/d was 1.0 to 5.0) in order to examine the effect of load position on the shear strength of the examined part.

Dimension of test beams and location of load points are shown in Fig.1. In E8 to E10 specimens, 2 ϕ6mm stirrups were used at intervals of 10 cm (web reinforcement ratio r = Av/(bo*s) = 0.00565) while 2D10mm stirrups were used at intervals of 5 to 10cm (r = 0.0285 to 0.0143) in the remaining part of the beam. In E12 to E15 specimens there was no web reinforcement in the examined part and 2D10mm stirrups were used at intervals of 10cm in the remaining part of the beam. Here the location of examined part was expressed by the distance (x) from the center of the part to the support. Concrete used in these specimens was lightweight concrete with non-pelletized type artificial lightweight aggregates. Maximum size of the aggregates was 15mm.

During the preliminary test in which one concentrated load was actually moved on the test beam, difficulty in examining the effect of movement of the load was recognized, and then the special test procedure as described above was developed. In each part of the beam subjected to moving load, direction of shear force is alternated according to the location of the load and it is one of the problems to be considered. But from the results of the preliminary test (See 3.4), presence of cross diagonal cracks due to the reversed load did not reduce shear strength of the part very much, and the neglection of the effect of reversed shear force in this test series may not affect much to the results obtained.

2.2 Effect of the location of load on shear strength

All the test beams failed in shear at the examined part except some beams in which distance from load point to examined part (a-x) is 0.5d. That is, in most beams a diagonal crack in the examined part developed into the major diagonal crack, and the beam failed in shear after this major diagonal crack propagated all through compression frange. In case of beams with (a-x) equal to 0.5d, major diagonal crack developed out of examined part inspite of there were much larger amount of web reinforcement.

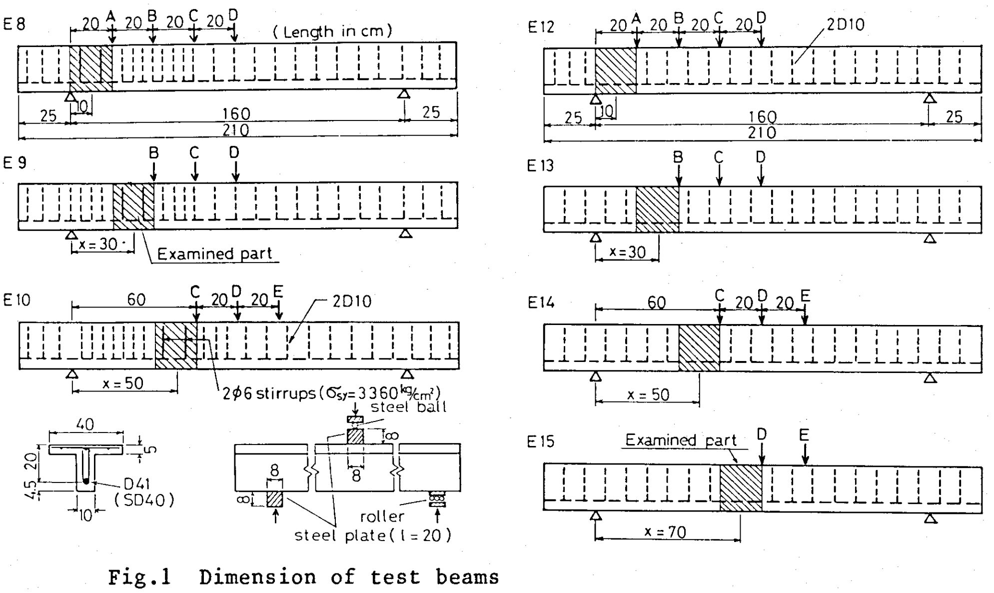


Fig.1 Dimension of test beams

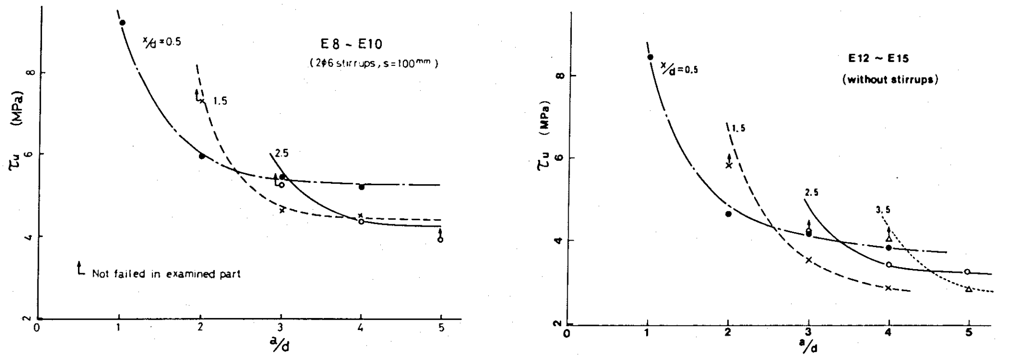


Fig.2 Shear strength in each part of beam

Expressing nominal shear strength by average shear stress at failure τ_u (= Su/(bo*d)), shear strength of each part of the beam with x/d equal 0.5 to 3.5 increased due to the approach of load to the part as shown in Fig.2. Especially when the value of (a-x) was less than 1.5d this increase in shear strength was remarkable. Fig.3 shows the relationship between the distance from load to examined part (a-x) and shear strength τ_u in beams E8 to E10. It is clearly seen from this figure that in the part near support (with small x/d ratio) shear strength will increase remarkably with the approach of load to the part and that the shear strength is larger in the part nearer to the support provided the value of a-x is constant.

This increase in nominal shear strength with the decreasing value of x/d and a/d is considered to be the effect of local compressive stress σ_y in the vertical direction introduced by concentrated load and reaction, because the presence of σ_y decreases principal tensile stress in the concrete [1]. Fig.4 shows measured stirrup strain in the examined part. It is clearly seen from this figure that the strain in stirrup σ_{sv} decreases when load is applied near to the examined part even though shear force applied is equal in every beam. These experimental results are considered to be supporting the discussion above.
The author believes that the conclusion here will also be able to apply to the ordinary concrete beams, qualitatively at least, because there is no evidence that the results obtained here have been affected by the characteristics of lightweight concrete.

2.3 Design considerations

Above mentioned characteristic, that is, nominal shear strength in any part of the beam will be increased due to the approach of the load to the part, have not been recognized in the previous researches and it should be reasonable to consider this characteristic in the design of reinforced concrete beams. In the practical design it may be more convenient to reduce design shear force accoding to the value of a and x assuming that shear strength is constant at every part of the beam rather than

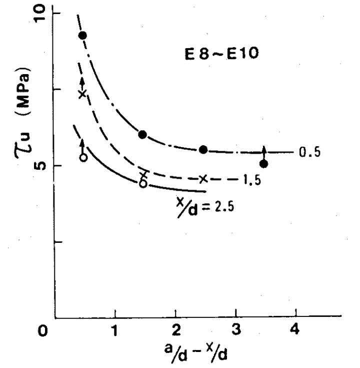


Fig.3 Effect of load position

to consider different shear strength with different value of a and x.

Relationship between nominal shear strength τu and (a-x) is as shown in Fig.3. Although the number and the range of experiment is not enough, it seems that in case of (a-x) greater than about 2.5d the effect of local compressive stress σy is very small and the location of load will practically not affect to the shear strength. So, in the design, it is possible to set shear strength at (a-x) equal to 2.5d ($\tau u,2.5d$) to the standard value, and reduce shear force in proportion of the ratio R = $\tau u,2.5d/ \tau u,a-x$, where $\tau u,a-x$ is shear stress due to the load applied at arbitraly location. Fig.5 shows the reduction factor R for each part of the beam. Eq.(1) is obtained to evaluate R assuming linear function between R and (a-x) for the simplicity.

$$R = 0.5*(1.0+(a-x)/1.5d) <= 1.0 \qquad (1)$$

It must be noted that Eq.(1) is applicable when load and reaction are applied to the beam so that vertical compressive stress (σy) will be introduced in the web concrete. To reduce shear stress due to the load acting within the distance 1.5d from considering part is basically corresponding to the well known fact that shear strength of the beam with smaller a/d ratio than about 3.0 is higher than that of beam with larger a/d ratio. Value of 1.5d in Eq.(1) is considered reasonable refering to the results of Kani's extensive work [2] or the discussion when CEB-FIP model code was revised [3].

Conclusions written in 2.2 are based on the experimental results from the loading test of relatively small scale specimens subjected to the stationary load. In order to confirm the adoptability of proposed design method under more realistic conditions, additional loading test of two large scale normal concrete beams (E50 and E60) were conducted under simulated moving load.
These two beams were desined to have 588 kN of shear failure load calculated by Eq.(1) and Eq.(2). Shear resistance of concrete in compression zone (τc)

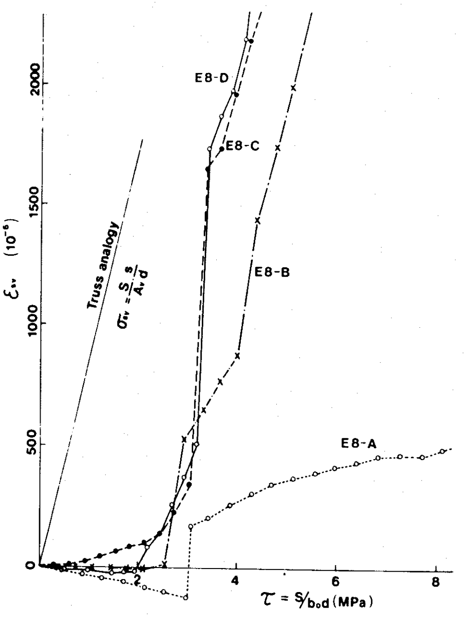


Fig.4 Strain of stirrups

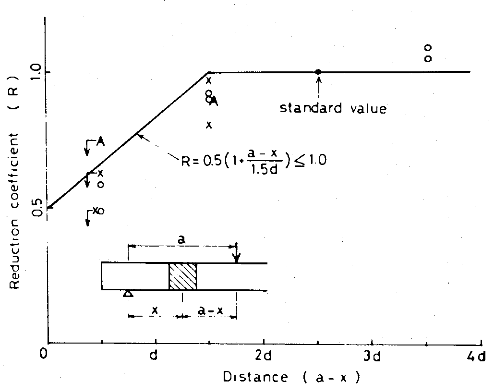


Fig.5 Reduction factor

was assumed to be $0.25*\sqrt{\sigma c}$ (MPa).

$$R*S = bo*d*(\tau c + K*r* \sigma sy) \qquad (2)$$

E50 was reinforced for shear mainly by bent up bars, while E60 was reinforced by stirrups only (Fig.6). In deciding the position where longitudinal bars were bent up, increase in tensile stress in longitudinal bars due to the development of diagonal cracks was not considered. The location of bent up point of each two bars was at the distance of 0.34d, 0.72d and 1.02d beyond the point where they were not required any more according to the conventional bending theory.
In the loading test of these beams five 1000 kN hydraulic jacks were installed at the interval of 50 cm. In the first step, 100 kN, for example, was applied by No.1 jack, then decreasing the load of No.1 jack to 50 kN, load of No.2 jack was increased to 50 kN at the same time. In the next step, load of No.2 jack was increased to 100 kN while load of No.1 jack was reduced to zero. By repeating these procedure in every load point, simulated moving load condition was created.

Stirrups and bent up bars in the middle part of E50 yielded by 588 kN (calculated failure load). After the intensity of moving load was increased to 736 kN, E50 failed in shear while load was being increased at load point 3. Maximum load at load point 3 was 703 kN.
In case of E60 reinforced with stirrups, some stirrups yielded by 588 kN and all stirrups crossed by diagonal cracks, except some in the vicinity of supprt, yielded under 686 kN. E60 did not fail in shear at the stage but it failed in flexure under 883 kN at load point 3.
The reasons of smaller shear strength of E50 comparing to E60 should be the facts that six longitudinal bars in E50 were bent up and the amount of longitudinal reinforcement was decreasing toward the support and that about one third of span length of E50 was reinforced only by bent up bars which can not restrain diagonal cracks to propagate horizontally along tension reinforcement.
It can be said that in both beams web reinforcement starts to yield under calculated failure load and all web reinforcement crossed by diagonal cracks yielded under 120% to 130% of calculated failure load, except some web reinforcement in the vicinity of support.

Although the yielding of shear reinforcement will not necessarily cause immediate shear failure of beam, it is very difficult to estimate the residual capacity beyond the yielding of shear reinforcement. On the other hand, as the width of diagonal cracks increases very rapidly after the yielding of shear reinforcement, yielding of shear reinforcement should be considered as an ultimate limit state, practically at least. It can be said that the shear strength of E50 and E60 almost coincided with the shear strength calculated by equation (2), if it is reminded that the "calculated strength" here is originally in the same meaning as described above.

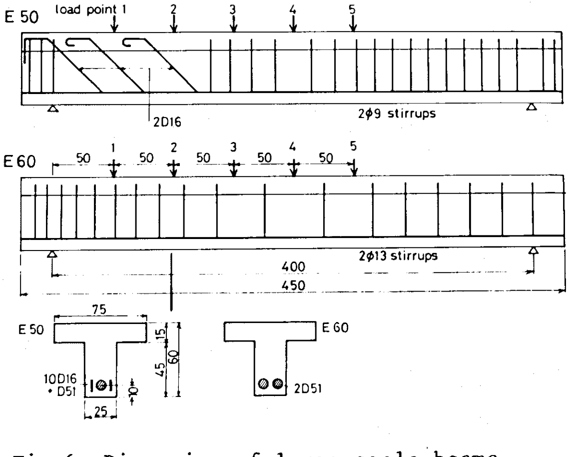


Fig.6 Dimension of large scale beams

Although X-shaped diagonal cracks developed in the middle part of the beams due to shear reversal accompanying the movement of load (Fig.7), any deterioration in shear strength caused by the X-shaped diagonal cracks was recognized in the experiments.

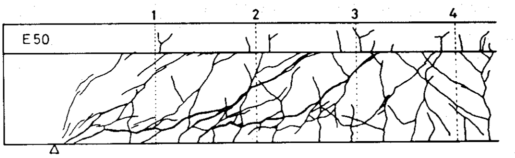


Fig.7 Diagonal crack in E50

These experimental results are supporting that the experimental method as described in 2.1 is appropreate to examine the effect of moving load on shear strength of the beam, and that in the design of web reinforcement of the beams reduced shear force can be used, provided load and reaction are applied in the manner which produce vertical compressive stress in the web. And reduction factor R by Eq.(1) might be used as a guide line.

3. Shear behavior of reinforced concrete beams under fatigue load

It has been confirmed that the failure mode and shear strength of beams tested under static loading are affected very much by shear span to effective depth ratio (a/d). As there are very few information concerning to the effect of a/d on shear behavior of beams subjected to fatigue load, fatigue test of beams with a/d between 2.0 and 6.36 was conducted.

3.1 Experimental program

Lightweight concrete with non-pelletized type artificial lightweight aggregates and high early strength cement was used. Test beams were cured seven days and tested when age of concrete was 15 to 58 days. Dimensions of test beams are as shown in Fig.8 .

In the loading test, specified upper limit load, corresponding to 43% to 83% of static shear failure load (Ps), was applied first statically to examine crack propagation and then repeated load was applied at the rate of 300 rpm. Diagonal cracks were developed in beams with a/d of 2.0 by the first static loading, but no diagonal crack was observed in beams with a/d from 4.0 to 6.36 at this stage. Lower limit load was kept to 10 kN which is corresponding to 17% to 25% of upper limit load. Loading test was stopped when number of cycles exceeded two million.

Results of fatigue loading test are shown in Table 1. Static shear failure load Ps was culculated by Eq.(3) and (4) based on the previous experimental results [7].

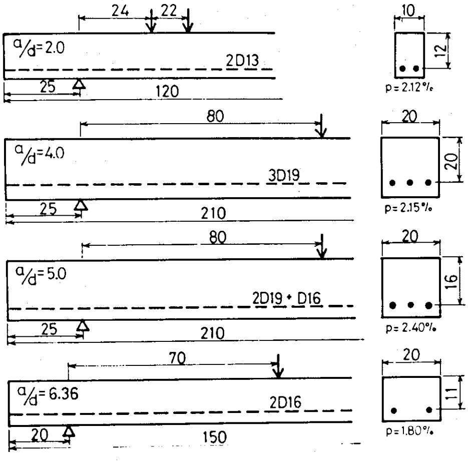


Fig.8 Beams for fatigue test

$$a/d = 2.0 \;;\quad \tau_u = Su/(bo*d) = 0.64*\sqrt{\sigma_c} \qquad (3)$$

$$a/d >= 4.5 \;;\quad \tau_u = 0.19*\sqrt{\sigma_c} \qquad (4)$$

3.2 Mechanism of fatigue shear failure

As shown in Table 1, beams with a/d of 6.36 failed in shear immediately with the development of diagonal cracks (diagonal tension failure) by 500 to 440,000 cycles of repeated loading with upper limit load (Pmax) equal to 65% to 78% of static shear failure load. In case of beams with a/d equal to 2.0, although diagonal cracks were developed during the first static loading, they were able to resist further loading by the mechanism similar to tied arch formed by the concrete above diagonal crack and tensile reinforcement. Failure of these beams (arch failure) were finally caused by the crushing of concrete in the compression zone or by fatigue fracture (breaking) of tensile reinforcement near the intersection point with major diagonal crack. In these beams, failure mode under fatigue load was almost the same as that under static load, except for the fracture of tensile reinforcement. But in beams with a/d value between 2.0 and 6.36, manner of fatigue failure was very complicated. That is, not only fatigue failure mode was different with that under static load, but also fatigue failure mode was different for different value of upper limit load. In case of beams with a/d equal to 5.0, for example, they were able to resist more than 400,000 cycles of additional loading after the development of diagonal cracks under Pmax of 0.63Ps to 0.67Ps, but they failed immediately after the development of cracks when Pmax was increased to 0.76 Ps and 0.83Ps.
Although shear failure under fatigue load is very complicated phenomena, it can be explained clearly if the effect of repeated load on diagonal cracking strength and on the capacity of arch mechanism is considered separately. Under repeated loading, diagonal crack will be developed due to fatigue of concrete in tension even if upper limit load is smaller than static diagonal cracking load (Pcs). In the beams with a/d of 5.0, for example, diagonal cracking load

Table 1 Summary of fatigue loading test

a/d	No.	σ_c (MPa)	Pmax (kN)	Pmax/Ps	τ (MPa)	Nc (10^4)	Nu (10^4)	Failure mode
2	FC1	34.6	(99.1)	(4.13)	(4.13)			Static, A
	FC2	35.1	(78.5)	(3.27)	(3.27)			Static, A
	FC4	35.1	39.2	0.43	1.64		> 200	
			49.0	0.54	2.04		> 200	
			58.8	0.64	2.45		95	A*
	FC5	31.9	53.9	0.62	2.25		17	A*
	FC6	31.9	53.9	0.62	2.25		15	A*
	FC7	38.3	49.0	0.52	2.04		59	A*
	FC8	35.3	58.8	0.64	2.45		14	A
4	FT1	41.2	(84.3)		(1.06)			Static, DT
	FT2	40.3	49.0	0.51	0.62	> 200	> 200	
	FT3	39.8	53.9	0.57	0.68	109	174	
	FT4	39.8	58.8	0.62	0.74	7	7	DT
5	FT18	36.2	(68.6)		(1.07)			Static, DT
	FT13	31.1	55.4	0.83	0.86	0.2	0.2	DT
	FT14	29.1	49.0	0.76	0.77	0.3	0.3	DT
	FT15	28.2	42.2	0.66	0.72	39	> 106	
	FT16	32.8	46.1	0.67	0.72	34	79	A
	FT17	31.1	42.2	0.63	0.66	241	> 241	
	FT19	35.1	47.1	0.67	0.74	6	73	A
6.36	FT5	34.4	(74.5)		(1.13)			Static, DT
	FT6	34.4	55.9	0.78	0.84	0.05	0.05	DT
	FT7	35.5	48.1	0.65	0.73	44	44	DT
	FT8	33.4	41.2	0.58	0.63	> 120	> 120	
	FT9	32.1	44.1	0.63	0.67	> 106	> 106	

τ : Average shear stress under Pmax.
A : Arch failure   A* : Arch failure (fracture of bar).
DT : Diagonal tension failure.

corresponding to 3000 cycles and 2,400,000 cycles of loading was 0.76Ps and 0.63Ps, respectively. That is, diagonal cracking load is not constant but different according to the number of load cycles. On the other hand, because of arch mechanism can be formed only after the development of diagonal crack and stress in concrete at the portion where it will constitute arch mechanism after diagonal cracking is relatively low, fatigue of concrete in arch mechanism before diagonal cracking could be ignored.

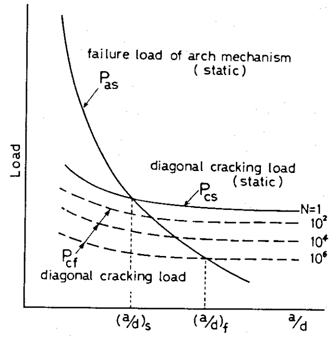


Fig.9 Concept of failure mode

According to the above discussion, failure mode should be different in the two regions, shown in Fig.9, divided by the line indicating static failure load of arch mechanism (Pas) provided the value of a/d is between (a/d)s and (a/d)f. Where, (a/d)f is the value of a/d at the intersection point of Pas curve and a curve indicating diagonal cracking load at specific load cycles, 1,000,000 cycles for example. In the region above Pcf curve and Pas curve, diagonal crack will be developed by repeated loading less than 1,000,000 cycles and beam will fail immediately after diagonal cracking. While in the other region above Pcf curve but below Pas curve, though diagonal crack will be developed by repeated loading, beam will be able to resist further loading and will finally fail by fatigue failure of arch mechanism.

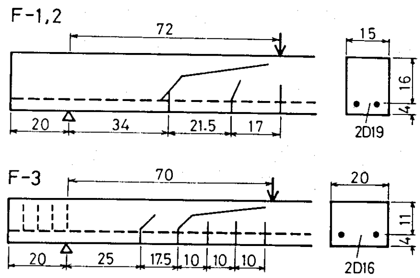


Fig.10 Artificial cracking

Load capacity of arch mechanism must be known to examine the hypothesis above. But in the beams with large a/d value, shear failure will take place almost simultaneously with the development of diagonal cracks under static loading and it is very hard to examine the capacity of arch mechanism experimentally. Then special test beams with artificial diagonal cracks were used to examine the load capacity of arch mechanism in the beams with a/d of 4.5 and 6.36 (Fig.10).

In the beam with a/d of 4.5, shear strength (τu = Su/(bo*d)) of arch mechanism was 90% to 108% of diagonal cracking strength (τc = Sc/(bo*d)) of identical beam but without artificial crack, while in the beam with a/d of 6.36, τu was very small and equal to 50% of τc.

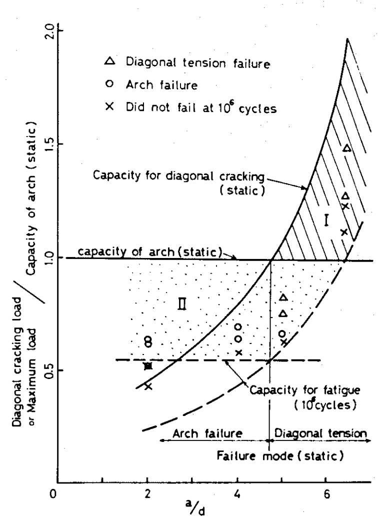


Fig.11 Fatigue failure mode

In Fig.11, estimated failure mode based on the above experimental results is comparerd to the failure mode observed in fatigue loading test. In region I and II estimated failure mode is diagonal tension failure and

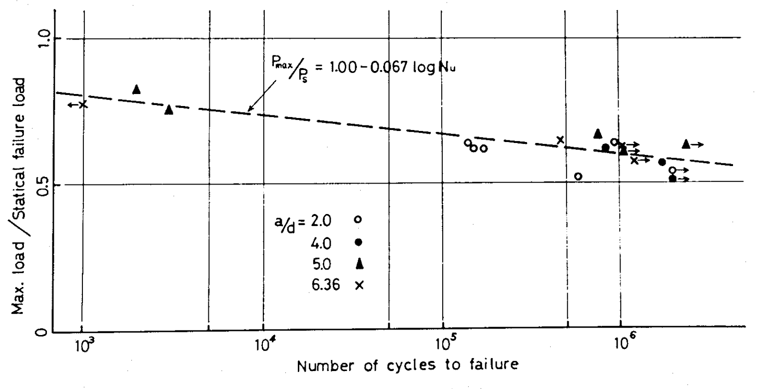


Fig.12 Results of fatigue test

arch failure respectively, and relatively good correspondence between estimated and observed failure mode is seen in the figure.

3.3 Fatigue strength

Assuming that the relationship between number of cycles at diagonal cracking (Ncr) and upper limit load (Pmax) is expressed by equation (5), α was determined to 0.066 using least squre method. And there was no significant effect of the value of a/d on α.

$$Pmax/Pcs = 1.00 - \alpha * \log Nc \quad (5)$$
$$Pmax/Pas = 1.00 - \alpha' * \log (Nu - Nc) \quad (6)$$

where,
Pcs : static diagonal cracking load
Pas : static failure load of arch mechanism

Assuming that the number of cycles affecting significantly to the fatigue of arch mechanism is (Nu - Nc), α' is determined to 0.071 in the same way as in Eq.(5), where Nu is the number of cycles at failure. It means strength of arch mechanism will be decreased to 57% of static strength by 1,000,000 cycles of fatigue loading. Significant effect of a/d on α' was not recognized also in this case.
Ratio of fatigue to static shear strength is not the same in diagonal tension

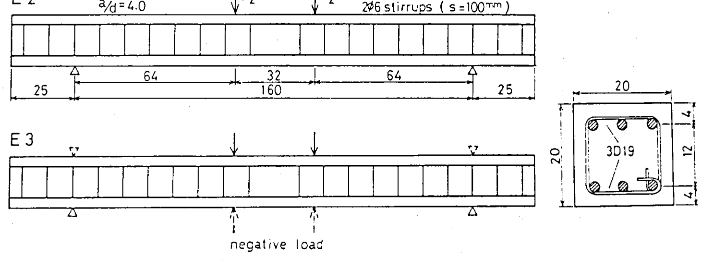


Fig.13 Beams for low cycle repeated load test

Table 2 Results of lowcycle repeated loading test

Loading	No.	Axial load (kN)	Strength of conc. (MPa)		Diagonal cracking (kN)	Failure load (kN)	Failure mode
			σ_c	σ_t			
One direction	E2	0	32.5	1.85	58.8	159.2	Shear,St yield
Reversed	E3	0	32.5	1.85	58.8	152.5	Shear,St yield
One direction	E5	193.3	35.3	1.85	107.9	166.2	Flex. Comp.
Reversed	E4	204.0	32.0	1.81	98.1	156.9	Shear

failure and in arch failure, but considering the variation in experimental results, this small difference can not be regarded as significant. Fig.12 shows the relationship between Pmax/Ps and Nu ignoring the effect of a/d. Fatigue shear strength at 1,000,000 cycles is about 60% of static shear strength. Lower limit load in the experiment was not more than 24% of upper limit load, and since it correspond to the case that shear force due to live load is more than three times larger than shear force due to dead load, the results obtained here should be in safer side for many cases.
Chang [8] reported based on his experimental results using ordinary concrete beams with a/d equal to 3.72 that shear strength decreased to 56% of static strength by 10,000,000 cycles of repeated loading and that between 1,000,000 and 10,000,000 cycles shear strength was almost constant. On the other hand, Fujita and Kaiho [9] reported that the ratio between fatigue and static strength of plane concrete was almost the same in compression, tension and bending test and that there was no significant difference in the compressive fatigue strength of ordinary concrete and that of lightweight concrete. Refering these results, effect of repeated load on shear strength might be considered almost the same for both lightweight concrete beams and ordinary concrete beams.

3.4 Consideration for web reinforcement

If web reinforcement is designed to total shear force, probability of fatigue fracture of web reinforcement may be very small, provided the value of allowable stress is reasonable. But if shear resistance of concrete is considered and web

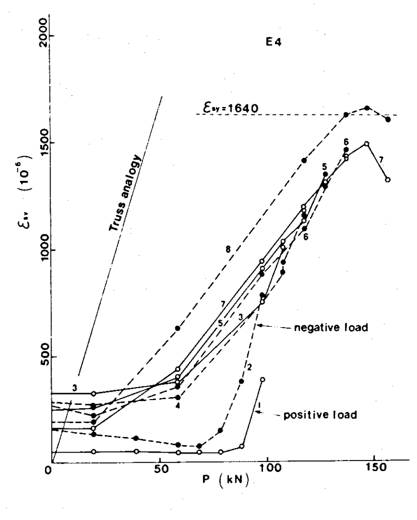


Fig.14 Strain of stirrups

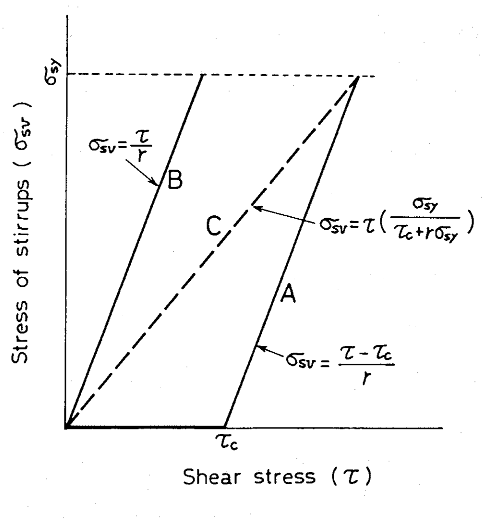


Fig.15 Stress of stirrups

reinforcement is designed to some part of shear force, as in ACI code, stress in web reinforcement should be carefully estimated to prevent fatigue fracture of web reinforcement.
To examine stress in stirrups, loading test of lightweight concrete beams with stirrups (Fig.13) was conducted. Small number of repeated load was applied statically. Summary of loading test is shown in Table 2. Measured stirrup strain is shown in Fig.14. Strain in stirrups gradually increased due to the repetition of load. After the development of diagonal cracks, stirrup strain increased almost proportional to the applied load, as shown in Fig.15 schematically. In the figure, line A represents the relationship between shear stress τ and tensile stress in stirrups σ_{sv} in the first loading. If very large over load, which cause high stress almost equal to yield point in stirrups, is applied just once, then stirrup stress will increase and relationship between τ and σ_{sv} will be expressed by line C. Where τ_c is shear stress at diagonal cracking, r is web reinforcement ratio and σ_{sy} is yield point of stirrups. It means if stirrup stress is calculated based on line A, probability of fatigue failure of stirrup may be very large, because actual stress in stirrup could be much higher than expected provided over loading is possible.

As the number of cycles of repeated load is very small in this experiment, it may not be appropreate to directly apply these results to the design of web reinforcement of the beams subjected to fatigue loading. But it can be said that the facts descrived above should be considered in the design of web reinforcement, at least.
Tentatively it is recommended to limit the stress in stirrups calculated by Eq.(7) not more than the allowable stress decided by fatigue strength of the reinforcement.

$$\sigma_{sv} = \tau * \sigma_{sy} /(0.55* \tau_c + r* \sigma_{sy}) \qquad (7)$$

4. Characteristics of lightweight concrete beams

4.1 Experimental program

Lightweight concrete with artificial lightweight aggregates (maximum size = 15 mm) and ordinary concrete with Fuji river aggregates (maximum size = 25 mm) were used for the comparizon. Dimension of test beams are as shown in Fig.16 . In the first series, rectanguler and tee beams with a/d ratio between 1.0 and 6.5 and without web reinforcement were used. In the second series, tee beams with stirrups were used. Value of a/d was 2.0 and 4.0, and the degree of web reinforcement $r* \sigma_{sy}$ was 1.14 kN (2 ϕ6mm, 10cm pitch) and 5.71 kN (2D10mm, 10cm pitch).

4.2 Shear failure mode of the beams without web reinforcement

According to the observation during loading test, both lightweight and ordinaly concrete beams failed in one of the two typical failure mode. In some beams diagonal cracks gradually developed from initiating flexural cracks in shear span but diagonal crack did not cause immediate failure of beams. Shear failure of these beams

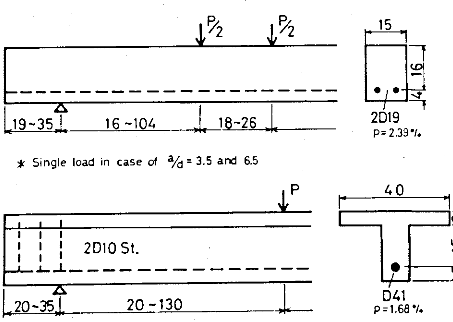


Fig.16 Dimension of test beams

were caused by crushing of concrete after the penetration of diagonal cracks deep into the compression zone (Shear compression failure). The other beams feiled suddenly due to the development of flexural crack into diagonal crack extending near to loading point (Diagonal tension failure). Failure mode in each test beam is shown in Table 3 and 4. Value of a/d where failure mode transfered from shear compression to diagonal tension ($(a/d)_t$) was approximately 3.5 and 4.5 for rectanguler and tee ordinaly concrete beams espectively, while $(a/d)_t$ for lightweight concrete beams was about 4.0 and 5.5 for rectanguler and tee beams respectively. Larger value of $(a/d)_t$ in lightweight concrete beams is considered due to the lower diagonal cracking strength caused by smaller aggregate interlock action in lightweight concrete,and it is not a substantial difference from ordinaly concrete beams.

4.3 Shear strength

In Fig.17 shear strength of lightweight concrete beams are compared with that of ordinally concrete beams, where shear strength is expressed by average shear stress at failure τ_u (= Su/(bo*d)). And converted shear strength $\tau_{u,300}$ was used to eliminate the effect of different compressive strength in each test beam.

$$\tau_{u,300} = \tau_u * \sqrt{29.43/\sigma_c} \quad (8)$$

Fig.17 is suggesting that there are three different regions concerning the ratio of shear strength of lightweight concrete beams and ordinaly concrete beams. In the first region, where a/d is very small, shear strength of lightweight concrete beam is less than 85% of ordinaly concrete beam. In the second region, where a/d is intermediate, shear strength of both beam is almost equal. And in the third region, where a/d is large, shear strength of lightweight concrete is about 75% to 85% of ordinaly beam. Although no significant difference in failure mode was observed between region I and region II, ratio of shear strength was clearly different in these two regions. It might be said that the effect of shear stress was dominant in

Table 3 Test results of rectanguler beams

a/d	Conc.	No.	σ_c (MPa)	τ_u (MPa)	$\tau_{u,300}$ (MPa)	Failure mode	Ratio* (%)
1.0	N	N12	31.2	9.89	9.63	F	85
	L	M12	29.8	8.09	8.02	S	
2.0	N	N2	31.0	3.06	2.97	SC	107
		N7	32.2	4.09	3.92	SC	
	L	M2	28.7	3.50	3.53	SC	
		M7	21.9	3.36	3.89	SC	
		B3	30.9	3.71	3.63	SC	
3.5	N	N1	31.0	1.43	1.39	DT	97 (DT88) (SC94)
		N3	30.9	1.67	1.63	SC	
		N4	37.3	1.53	1.36	DT	
	L	M1	28.7	1.20	1.21	DT	
		M3	28.1	1.53	1.58	SC	
		M4	33.4	1.58	1.48	SC	
4.5	N	N5	32.2	1.42	1.36	DT	76
		N6	32.2	1.41	1.35	DT	
		N9	32.0	1.49	1.40	DT	
	L	M5	21.9	0.93	1.06	DT	
		M6	22.9	0.90	1.03	DT	
		B1	29.9	0.94	0.93	DT	
		B2	26.1	1.02	1.13	DT	
6.5	N	N13	35.2	1.44	1.31	DT	78
	L	M13	29.4	1.02	1.02	DT	

N : Normal weight conc. L : Ligttweight conc.
F : Flexural S : Shear SC : Shear comp.
DT : Diagonal tension.
* : Ratio of u,300 between L and N beam.

Table 4 Test results of T-beams

a/d	Conc.	No.	σ_c (MPa)	τ_u (MPa)	$\tau_{u,300}$ (MPa)	Failure mode	Ratio (%)
1.0	N	TN1	33.2	11.38	10.69	S	
	L	E12A	28.4	8.48	8.64	S	81
2.0	N	TN2B	29.7	5.29	5.26	S	
	L	E16B	31.4	4.61	4.47	S	85
3.0	N	TN3	29.9	2.94	2.91	SC	
	L	E16C2	28.9	3.19	3.21	SC	110
4.0	N	TN4	31.0	1.96	1.90	SC	
	L	E16D	32.7	1.96	1.86	SC	98
5.0	N	TN5	31.9	1.74	1.67	DT	
	L	E16E	33.9	1.96	1.82	SC	109
6.5	N	TN6	30.8	1.72	1.68	DT	
	L	E16F	26.6	1.35	1.42	DT	85

region I (Shear proper), while in region II, the effect of compressive stress was dominant for the failure of concrete in compression zone. As shown above, there are some differences in the behavior of lightweight concrete beams with that of ordinary concrete beams, and the experimental results from lightweight concrete beams might not be applied directly to ordinary concrete beams, especially if a/d ratio is near the transition point of failure mode. But these differences will not affect significantly to the behavior of the beams in the actual structures, because there are always some stirrups to prevent sudden shear failure due to diagonal cracking, and the mode of shear failure of actual beams is restricted.

Table 5 Effect of web reinforcement

	a/d	No.	$r\sigma_{sy}$ (MPa)	σ_c (MPa)	τ_u (MPa)	$\Delta\tau$ (MPa)	$\Delta\tau/r\sigma_{sy}$
L	2.0	E16B	0	31.4	4.61	-	-
		MS3	1.14	33.0	5.81	1.20	1.05
		MS4	5.71	33.0	7.24	2.58	0.46
	4.0	E16D	0	32.7	1.96	-	-
		MS1	1.14	32.5	3.90	1.94	1.71
		MS2	5.71	33.6	5.28	3.32	0.58
N	2.0	TN2B	0	29.7	5.29	-	-
		NS3	1.14	34.5	6.50	1.22	1.07
		NS4	5.71	33.1	8.58	3.30	0.58
	4.0	TN4	0	31.0	1.96	-	-
		NS1	1.14	32.0	4.27	2.30	2.02
		NS2	5.71	34.1	6.13	4.17	0.73

4.4 Effect of web reinforcement

Results of loading test are summarized in Table 5. Except for ordinaly concrete beam NS4 with a/d of 2.0 and $r^* \sigma sy$ of 5.71 MPa, all beams failed in shear. Beams with $r^* \sigma sy$ of 1.14 MPa failed after the yielding of stirrups, and beams with $r^* \sigma sy$ of 5.71 MPa failed before the yielding of stirrups. Considering the difference in shear strength ($\Delta\tau$) between beams with stirrups and beams without stirrups to be the effect of stirrups, effect of stirrup is larger in the beam with larger a/d for both lightweight and ordinaly concrete beams. And efficiency of stirrup is decreasing with increasing degree of web reinforcement ($r^* \sigma sy$). It is also clear that effect of stirrup is smaller in lightweight concrete beams. Ratio of $\Delta\tau$ of lightweight concrete beam to ordinaly concrete beam is 98% to 85% for $r^* \sigma sy$ of 1.14 MPa and 79% for $r^* \sigma sy$ of 5.71 MPa. The deficiency of stirrups in lightweight concrete beam is more considerable for largr $r^* \sigma sy$. Although these characteristics should be considered in the design of web reinforcement, effect of such characteristics on the relative change of shear strength accompanying the movement of load position discussed in 2. is not considered significant.

5. Conclusions

Following conclusions were obtained based on the experimental works related to shear behavior of reinforced concrete beams subjected to moving load and fatigue load.

(1) It seems essential to pay attention to the shear strength in each part of the beam for the rational design of the beams subjected to moving load.

Shear strength in each part of beam, loaded and supported directly, increased when load was applied near the considering part, especially within a diatance 1.5d from the part. Although

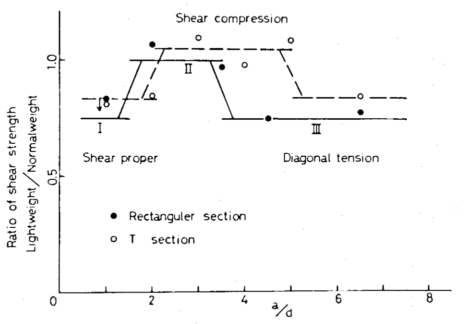


Fig.17 Comparizon of shear strength

such increase in shear strength was larger in the part near support, the same behavior was observed at the part in mid span.

(2) In designing the beam loaded and supported directly, it is possible to reduce design shear force utilizing the characteristics above. Reduction factor R by Eq.(1) may be used as a guide line.

(3) Shear failure mode of the beams subjected to fatigue load was different with that of the beams subjected to static load depend on the value of a/d. Failure mode under fatigue loading was changed depend on the value of upper limit load even if value of a/d was kept constant.

(4) Although fatigue shear failure is a complicated phenomena, it can be explained clearly if the effect of repeated load on diagonal cracking strength and on the strength of arch mechanism which is formed after diagonal cracking is considered separately.

(5) Shear strength of lightweight concrete beam was decreased to 55% to 65% (average 60%) of static strength by 1 million cycles of repeated loading. No significant effect of different failure mode on fatigue strength was observed.

(6) These conclusions are obtained from the results of loading test of lightweight concrete beams. Characteristics of lightweight concrete beams was also examined and no substantial difference from ordinary concrete beams was recognized.

Acknowledgement

This project was performed in and supported by the Department of Civil Engineering of the University of Tokyo. The author express his sincere thanks to Dr. Masatane Kokubu and Dr. Hajime Okamura for many useful advices as the superviser.

References

1) Ferguson, P.M.: Some implications of recent diagonal tension tests, ACI Journal, Aug. 1954.
2) Kani, G.N.J. : How safe are our large reinforced concrete beams ?, ACI Journal, Mar. 1967.
3) C.E.B. : Bulletin D'Information No 109, Apr. 1975
4) ACI-ASCE Committee 426 : The shear strength of reinforced concrete members, Journal of ST division, Proc. of ASCE, Vol.99, No.ST6, June, 1973.
5) Bresler, B., MacGregor, J.R. : Review of concrete beams failing in shear, Proc. of ASCE, ST, Feb. 1967.
6) Kokubu, M., Higai, T. : Shear failure of reinforced concrete beams subjected to repeated load, CAJ 25th general meeting, June, 1971.
7) Higai, T. : On the shear strength of lightweight concrete beams, Concrete Libraly No.24, JSCE, Oct. 1969.
8) Chang, T.S., Kesler, C.E. : Fatigue behavior of reinforced concrete beams, ACI Journal, Aug. 1958
9) Fujita, Y., Kaiho, Y. : Fatigue behavior of concrete in compression, tension and bending, CJA 21th General meeting, June, 1967.
10) Kobayashi, K., Ito, T., Shibata, K. : Fatigue behavior of lightweight concrete in compression, Concrete Libraly No.24, JSCE, Oct. 1964