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# Shear Transfer By Aggregate Interlock

By
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Synopsis : In a test program, comprising 44 specimens, the nature of shear transfer across prepared cracks by aggregate interlock mechanism was further explored. Within a narrow range aggregate shapes and sizes had no discernible effect upon the mechanism. Shear displacements under monotonic and cyclic loading were found to be approximately proportional to the preselected width of preformed cracks. Thus crack widths affected predominantly the stiffness of aggregate interlock mechanism. The restraining stresses required to prevent the unrestricted opening of a crack, while interface shear stresses were being transferred, were found to be independent of aggregate shape or size and of selected crack widths. The shear stress - restraining stress relationship was approximately linear up to a shear stress of 1000 psi (70 kgf/cm$^2$) and this corresponded with a mean coefficient of friction of 1.7.

Keywords: aggregate interlock; aggregate shape and texture; beams (supports); concretes; crack width and spacing; cracking (fracturing) cyclic loads; joints (junctions); shear stress; stiffness; stress transfer; stresses; tests.

# shear in reinforced concrete

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## INTRODUCTION

When a crack is developed in a concrete mass the surfaces of the crack are usually rough and irregular. The majority of the coarse aggregate particles remain embedded in one or the other of the crack faces. When this crack forms along a continuous plane a parallel displacement in this plane is possible and, therefore, projecting particles from one face of the crack come into contact with the matrix of the other face. Further movement is then restricted by the bearing and friction of the aggregate particles on the crack surface. Provided that restraint is available, to prevent large increases in the crack width, substantial shear forces can be transmitted across the crack interface. This is aggregate interlock action. It is usually defined in terms of the average shear stress, the shear displacement in the plane of the interface and the width of the crack.

In a number of situations aggregate interlock has only recently been recognised as a viable shear transfer mechanism. Contraction joints in concrete pavements were probably the first ones in which aggregate interlock in combination with dowel bars were relied upon for interface shear load. (1, 2) Cracks can also easily form at the interface of precast and cast in situ components where monolithic action is expected. Direct shear load must be considered in such a situation. (3, 4, 5, 6) Similar conditions can exist at construction joints in cast in situ concrete, in particular in horizontal construction joints across shear walls which have to resist large lateral forces. (7) Shear displacement along diagonal tension cracks, caused by shear forces in reinforced concrete beams, have also been observed. The resulting interface shear transfer by aggregate interlock has been found (8, 9) to account for a major share of the shear resistance in beams without web reinforcement. Design rules for shear friction, largely based on the work of Mast (10) and Mattock (11) have now been incorporated in the ACI Building Code (12).

The scope of this study was to continue the investigation into the fundamental aspects of shear transfer by aggregate interlock.

A total of 44 specimens were tested to examine the effect of aggregate shape, size and the crack width, using monotonic and cyclic static loading.

## TEST SPECIMENS AND LOADING

The dimensions of the test specimen, similar to that used by Mattock et al., (11) are shown in Fig.1. The contact area, shown shaded, over which the shear stresses were transmitted was 33.7 $in^2$ (217$cm^2$). Fig.2 shows the formwork used for the simultaneous casting of two specimens. Some reinforcement was provided to control possible cracking away from the test surface. The bolt inserts, seen in Fig.2, were used to introduce a controlled tension force at right angles to the shear plane. They did not pass through the shear plane but attached the two concrete blocks to the stiff frame surrounding the specimen.

The load, acting across the shear plane, was introduced to one half of the specimen which was free to move vertically, while the other half was rigidly mounted in the test frame. The mounting arrangement for the moving part was such that the crack width could be controlled within 2% of the required value. Shear displacements and crack widths were measured at both faces of the specimen with demountable mechanical strain gauges. These gave the change of distance between stainless steel locating discs attached to the concrete surface at 2 in (5.08 cm) centres. Details of the test rig and test procedure are reported elsewhere (14).

Ordinary Portland cement and good quality alluvial gravel and sand from the Canterbury district of New Zealand were used for making the concrete, which had a four inch (10cm) cube strength of approximately 5300 psi (370 kgf/$cm^2$) at the time of testing. Only three types of coarse aggregate were used, 3/8 in (9.5 mm) and 3/4 in (19 mm) round maximum size and 3/4 in (19 mm) crushed maximum size. To speed up testing sometimes calcium chloride was added in making the concrete so that testing could be carried out 48 hours after casting. The more important properties of the specimens are summarised in Table 1. The load was introduced in approximately 20 equal increments and a test was terminated when the specimen could carry no further load or when shear displacements could no longer be measured or when the crack width exceeded the desired value by 50%. During the test crack widths were adjusted, before a load increment, but only when the deviation from the specified value exceeded 5%.

The specified nominal crack widths used in the tests were 0.005 in, 0.01 in or 0.02 in (0.13, 0.25 and 0.51 mm). In a few specimens the width of the preformed crack was varied, the applied shear stress to crack width ratio being kept constant.

## TESTS WITH CONSTANT CRACK WIDTH

In 27 tests the load was monotonically increased till failure or the termination of the test because of other reasons. For three types of aggregate and three different crack widths, the load displacement relationships were established. Typical observations are shown in Fig.3, which records the reponse of three specimens with 3/4 inch

(19 mm) round maximum size aggregate for three different crack widths.

The first significant trend which emerged from the testing was the effect of sedimentation and water gain under the coarse aggregate particles, situated in the top of the concrete, when the specimen was cast, see Fig.2. The shear displacement readings were significantly and consistently larger at the "top" side of the specimen when compared with measurements on the "bottom" side. This is clearly evident in Fig.3,where the shear stress - shear displacement relationship has been approximated by a bilinear one.

From a comparison of all responses it becomes evident that the aggregate size or shape used in this study had no noticeable effect. Specimens with 3/8 in (9.5 mm) maximum size aggregate failed suddenly when the shear stress reached approximately 1100 psi (80 kgf/cm$^2$) as opposed to a more gradual failure when 3/4 in (19 mm) size aggregate was used. Crack widths could not be controlled when the load was in excess of 1000 psi (70 kgf/cm$^2$). Specimens with small crack widths usually failed more suddenly than those with 0.02 in (0.51 mm) crack width.

The trends shown in Fig.3 are representative of all other tests. Up to a shear stress of approximately 300 psi (21 kgf/cm$^2$) the stiffness of the specimens increased to a maximum value which was then maintained to shear stress level of approximately 900 psi (63 kgf/cm$^2$). Further loading caused a degradation in stiffness.

A bilinear regression analysis was used to express the two phase behaviour of all specimens tested. This is shown in Fig.4. The shaded area includes 75% of all the individual results. The limits are expressed as a percentage of the mean shear stress. The change of stiffness at low load intensity is due to the "initial looseness of fit". (2) A certain displacement must occur before the aggregate particles, projecting across the crack, can firmly bear against the matrix of the opposite face. Once this bearing is established, a linear elastic response, represented by the steeper line, was encountered. The origin of the first line does not coincide with the origin of coordinate system because first a "no load displacement" must occur. (13) After the formation of a tension crack, particles are not in contact with each other and therefore only a very small shear load is required to establish the first contact and hence resistance against further shear displacement is small. The larger the initial crack width, the larger the "no load shear displacement".

## CYCLIC LOAD TESTS

In most structural elements the load is of a fluctuating nature. Therefore it is relevant that the response of the aggregate interlock mechanism under cyclic loading without reversals should also be examined.

The fatigue strength of interface shear transfer in concrete pavements has been studied. (12) The effectiveness of shear transfer for low intensity, approximately 30 to 40 psi (2 to 3 kgf/cm$^2$), loading of up to a million cycles was found to be drastically affected by the width of the crack and to a lesser degree by the size, shape and hardness of the aggregates.

In this study, load intensities more likely to be encountered during severe seismic disturbances were applied to the specimens. Therefore shear stresses a little over 800 psi (56 kgf/cm$^2$) were applied 33 times with time intervals after certain cycles to allow detailed measurements to be made. Concrete with 3/4 in (19 mm) or 3/8 in (9.5 mm) maximum round aggregate size was used in nine tests in which only the crack width was varied, as in the previous tests. Three to four hours were required to complete the testing of one specimen.

At no stage was a sudden breakdown of aggregate interlock action observed. The failure was similar to that encountered in the tests with monotonic loading. However, as could be expected, there was an accumulation of residual shear displacements with progressing loading. These increased proportionally with the crack width. In specimens with 0.02 in (0.51 mm) crack width, the testing became impractical after the 17th cycle. In each test the load in the last cycle was increased till failure occurred as in the previous tests with monotonic loading.

Crack surfaces after the testing were, as expected, heavily striated. A large quantity of crushed matrix and smaller aggregate particles could be seen. The surface irregularities were worn down and edges of aggregate indentations were rounded off. Again no difference in behaviour of the specimens with different coarse aggregate sizes were observed.

For a number of fully instrumented load cycles the bilinear shear stress - shear displacement relationship was determined as described earlier. Where more than one test was carried out for a given constant crack width, these bilinear responses were averaged. This enabled at least a qualitative comparison of the responses to cyclic loading to be made for the three selected crack widths. The results, which are self-explanatory, are presented in Fig.5, Fig.6 and Fig.7. Between the 2nd and 17th cycles and similarly between the 18th and 32nd cycles, no shear displacements were measured for individual load cycles.

As the number of load cycles increased the lower portions of curves become less linear. The predominant feature of these bilinear curves is the increased stiffness of the mechanism as cyclic loading progressed. From a comparison of the three responses it is evident that, with respect to the first loading, 210%, 280% and 320% increase of stiffness occurred in specimens with a 0.005 in, 0.010 in and 0.020 in crack width respectively. When comparing the residual shear displacements for the three cases, shown in Fig.5, Fig.6 and Fig.7, the different horizontal scales used in each case should be noted.

The loading, 830 psi (59 kgf/cm$^2$), was extremely severe. For the concrete strength used shear stresses of this magnitude, approximately $13\sqrt{f'_c}$ psi, are not likely to be encountered because the structure would probably show distress due to other causes. Moreover in real structures the constant crack width could not be maintained over such a large range of shear stresses. It is also to be noted that the load was applied in one direction only.

There are situations where the cyclic loading may be associated with load reversals. It is likely that a very much larger strength degradation and accumulation of residual shear displacements would occur. In tests of construction joints, in which the cracks of the shear plane were neither preformed nor controlled with respect to width, such phenomena were observed. (7)

TESTS WITH VARIABLE CRACK WIDTH

Tests with monotonic or cyclic loading and constant crack widths provide useful information with respect to behaviour but they do not represent well situations encountered in practice. It is more likely that as the load intensity increases on the aggregate interlock mechanism the crack width will also increase. Indeed, in beams the cracks increase as the tensile steel stresses increase. It was, therefore, decided to conduct a few tests in which the ratio of load to crack width was to be kept constant at the rate of 100 psi/0.002 in ($13.8\ kgf/cm^2$ / 0.1 mm).

In these tests the load was increased at 50 psi ($3.5\ kgf/cm^2$) increments, but the crack widths were adjusted only at every second increment because a crack, set before an increment, always increased only slightly during the application of the incremental load. At higher loads little adjustment was required as the crack width increased, of its own accord, approximately at the desired rate.

The majority of specimens failed when a sudden increase of crack width and a breakdown of aggregate interlock shear transfer, as manifested by a large increase in shear displacement, was observed. An examination of the crack surface showed more damage than in specimens with constant crack widths. A larger amount of ground material from the matrix and dislodged small aggregate particles were found. In spite of difficulties encountered with the adjustment of crack widths, while the load was maintained, there was little observed scatter in the shear stress - shear displacement relationships both individually and between tests.

Fig.8 shows the result obtained from a regression analysis carried out for all but one of the specimens. The limits enclose 75% of all test results. A comparison of individual tests showed that neither strength variation nor aggregate size used had a discernible effect upon the response. Upon this curve the results from the previous "constant crack width tests" (Fig.4) have also been transposed to enable a comparison to be made. The heavy broken line connects the appropriate stress values for the three distinct crack widths used in the tests. It reveals the same form as the relationship obtained from the "variable crack width tests". The latter, however, show considerably larger shear displacements at any given shear stress level. It is believed that this is mainly due to the test procedure and in particular the technique of crack width adjustments during the tests, which could not be controlled with complete satisfaction. The tests demonstrate once more the drastic loss of stiffness in interface shear transfer when the crack width is allowed to increase.

## TESTS WITH RESTRAINING FORCES

From the first series of tests and the work of others (11) it became evident that considerable restraining forces, acting at right angles to the shear plane, are required to maintain a crack width at its chosen magnitude, while interface shear load is being applied. To measure this, a load cell was designed and built into the modified test rig and a new series of tests was carried out. The system was not stable enough to carry out tests with cyclic load or variable crack width and so monotonic load was applied to these restrained specimens, while the crack width was held constant.

As in previous tests the width of the cracks tended to increase with increased load and so after every two or three load increments adjustments had to be made to reduce the crack width to the specified magnitude. The restraining force did not change during small load increment, but it increased suddenly whenever crack width adjustments were made. Typical results are shown in Fig.9. It is seen that for an approximately constant restraining force several different shear stress intensities were obtained. For all individual specimens and for selected groups of specimens a logarithmic regression analysis was performed. (14) Results of this are also shown in Fig.9.

From a comparison of different groups of specimens in which either the aggregate size (3/4 in or 3/8 in) or the crack width (0.005, 0.010 and 0.020 in) was kept constant, it became evident that none of these parameters has a distinct effect upon the restraining force required to maintain a given shear stress transfer by aggregate interlock. This is demonstrated by Fig.10, which shows the curves, obtained by regression analyses, for each group and the magnitude of the particular parameter which was the same for all specimens in that group.

These results are similar to those obtained by Mattock et al.(11), but a direct comparison cannot be made. In the latter tests the restraining force was provided by reinforcement which crossed the preformed crack. The width of the crack was not controlled, but it was permitted to increase till yielding in the reinforcement set in or failure of the interlock mechanism occurred.

It may be seen in Fig.10 that for design purposes the mean shear stress - restraining stress relationship could be approximated by a straight line corresponding with a coefficient of friction of $\mu = 1.7$ . When the restraining force is provided by reinforcement the ACI Building Code (12) recommends $\mu = 1.4$ . It is to be noted, however, that in the latter case shear forces can also be transferred by the dowelling action of the reinforcement.

## CONCLUSIONS

From an experimental study of the nature of shear transfer by aggregate interlock action, the following observations emerged :

1. The shear stress - shear displacement relationship does not seem to be affected by either the size or the shape of the coarse aggregate particles used in making the concrete. It should be noted, however, that the maximum aggregate size varied only between the narrow limits of 3/8 in (9.5 mm) and 3/4 in (19 mm).

2. The response of coarse aggregate particles is appreciably influenced by their position relative to casting of the concrete. Large shear displacements occur when the embedment of particles in the top of the concrete is weakened by water gain and sedimentation.

3. The largest single factor affecting shear displacement is the width of a crack across which shear stresses are to be transferred. Within the ranges considered, the shear displacement was found to be approximately proportional to the selected crack width.

4. For a constant crack width the response could be satisfactorily represented by a bilinear relationship. Initial looseness of fit of aggregate particles accounts for the relatively small stiffness of the mechanism at low loads.

5. The magnitude of the constant crack width was found to dominate the response of test specimens also under cyclic loading of relatively high intensity. The accumulation of residual shear displacement after each load cycle was proportional to the preselected crack width. The stiffness of aggregate interlock mechanism during repetitive loading was two to three times the stiffness observed during first loading.

6. Tests, in which the crack width increased proportionally with the load, verified that the stiffness of the mechanism gradually decreased as the shear stress across the interface increased. This is the situation most likely to be encountered in structures.

7. The restraining stress required to prevent the opening of a preformed crack, while interface shear is being transferred, was found to be independent of aggregate shape and size and also of crack width.

8. The mean ratio of shear stress to restraining stress, i.e. the coefficient of friction in these tests, was 1.7 .

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REFERENCES

1. Colley, B.E. and Humphrey, H.A., "Aggregate Interlock at Joints in Concrete Pavements", Portland Cement Association Research and Development Laboratories, Bulletin, D124, 1967, p.18.

2. Nowlen, W.J., "Influence of Aggregate Properties on Effectiveness of Interlock Joints in Concrete Pavements", Portland Cement Association Research and Development Laboratories, Bulletin D139, 1968, p.7.

3. Birkeland, P.W. and Birkeland, H.W., "Connections in Precast Concrete Construction", ACI Journal, Proceedings, Vol.63, No.3, March 1966, pp.345-368.

4. Hanson, N.W., "Pre Cast - Prestressed Concrete Bridges 2. Horizontal Shear Connections", Portland Cement Association Research and Development Laboratories, Bulletin D35, 1960, p.21.

5. Anderson, R.A., "Composite Designs in Precast and Cast-in-Place Concrete", Progressive Architecture, V.41, No.9, Sept.1960, pp.172-179.

6. Gaston, J.R. and Kriz, L.B., "Connections in Precast Concrete Structures - Scarf Joints", Journal Prestressed Concrete Institute, Vol.9, No.3, June 1964, pp.37-59.

7. Phillips, M.H., "Horizontal Construction Joints in Cast-in-Situ Concrete", M.E. Report, University of Canterbury, Christchurch, New Zealand, Feb.1972, p.93.

8. Fenwick, R.C. and Paulay, T., "Mechanisms of Shear Resistance in Concrete Beams", Proceedings, ASCE, V.94, No.ST10, Oct.1968, pp.2235-2350.

9. Taylor, H.P.J., " Further Tests to Determine Shear Stresses in Reinforced Concrete Beams", Cement and Concrete Association (London), Technical Report TRA 438, 1970, p.27.

10. Mast, R.F., "Auxiliary Reinforcement in Concrete Connections", Proceedings ASCE, Vol.94, ST6, June 1968, pp.1485-1504.

11. Mattock, A.H., Hofbeck, J.F., and Ibrahim, I.O., "Shear Transfer in Reinforced Concrete", ACI Journal, Proceedings, Vol.66, No.2, Feb.1969, pp.119-128.

12. -- ACI Standard 318-71, Building Code Requirements for Reinforced Concrete, American Concrete Institute, 1971, p.78.

13. Fenwick, R.C., "The Shear Strength of Reinforced Concrete Beams", Ph.D.Thesis, University of Canterbury, Christchurch, New Zealand, 1966, p.359.

14. Loeber, P.J., "Shear Transfer by Aggregate Interlock", M.E.Thesis, University of Canterbury, Christchurch, New Zealand, 1970, p.163.

TABLE 1 - PROPERTIES OF TEST SPECIMENS

| Type and Size of Aggregate | Crack Width | | Number of tests * | Average Cube Strength ** | |
|---|---|---|---|---|---|
| | inch | mm | | psi | $kgf/cm^2$ |
| 3/8 R | 0.005 | 0.13 | 1 | 5290 | 372 |
| " | 0.010 | 0.25 | 4 (1) | 5340 | 375 |
| " | 0.020 | 0.51 | 1 | 5290 | 372 |
| 3/4 R | 0.005 | 0.13 | 4 (1) | 5070 | 356 |
| " | 0.010 | 0.25 | 9 (4) | 5200 | 366 |
| " | 0.020 | 0.51 | 7 (3) | 5220 | 367 |
| 3/4 CR | 0.005 | 0.13 | 2 | 5600 | 394 |
| " | 0.010 | 0.25 | 5 | 5630 | 396 |
| " | 0.020 | 0.51 | 3 | 5530 | 389 |
| 3/4 R | variable | | 7 | 5410 | 380 |
| 3/8 R | variable | | 1 | 5450 | 383 |

R = Round Aggregate

CR = Crushed Aggregate

* The numbers in brackets indicate cyclic loading tests.

** Determined on three 4 in (10cm) cubes.