Behaviour of Pressure Confined Concrete in Cyclic Loadings

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Abstract

An on-going experimental program to study the short-term mechanical behavior of pressure confined cylindrical concrete specimens subjected to monotonic or cyclic loadings is reported. Tests involve monotonic or cyclic compression along the longitudinal axis of the specimen, while lateral confining pressure is maintained constant ($\sigma_1 > \sigma_2 = \sigma_3$). Low-cycle fatigue behavior of the specimens is studied by applying high maximum stress levels or large stress differentials in each cycle or both. Parameters investigated and varied are the confining pressure, cyclic stress range, axial strain rate and concrete strength. Test results are reported and behavioral trends discussed.

1. Introduction

Confined concrete in compression is known to manifest higher strength and ductility than concrete in uniaxial compression. In structural members, confinement of concrete may be present through closely spaced transverse reinforcement and from adjoining concrete elements. Therefore in critically stressed areas such as the bases of concrete columns and bridge piers, beam-column joints and hinges, substantial lateral confinement is always provided. Also, behavior of confined concrete under cyclic loads is important in the design for dynamic effects on structures due to earthquakes, winds and waves.

Safety and economic reasons dictate that concrete structures such as nuclear containment pressure vessels and offshore structures be accurately analyzed considering the full range of nonlinear behavior for cyclic loadings. Application of such analyses are often limited by the inadequacy of material models in representing the behavior of multiaxially loaded concrete subjected to load reversals and low-cycle fatigue. Work presented in this paper is part of a continuing research program funded by the National Science Foundation to study such behavior.

2. Literature Review

At present, ample information is available on the behavior of monotonically loaded concrete under triaxial conditions, while only limited information on triaxial cyclic behavior of concrete can be found.

Miller and Malliaros [1] carried out low cycle fatigue studies using ϕ2" x 4" concrete cylinders. Maximum confining pressure reached was 1,200 psi. The axial load was cycled between preset limits at a rate of 0.3 inches/minute. The following observations were reported:

(a) concrete strength increased with an increase in confining pressure. This increase was almost linear with the strength increased by about 5.8 times the confining pressure;

(b) as load cycles were applied, the hysteresis loops generally increased in area and reached to a larger peak strain. The area bounded by the loop was quite small until the specimen was very close to failure;

(c) strength of concrete decreased as the number of cycles applied to the specimen increased.

Costello [2] performed threshold fatigue tests on ϕ2" x 6" concrete cylinders with confining pressure levels of 0, 500 and 1,000 psi. He concluded that:

(a) The stress-strain relations for confined concrete possessed an envelope. This envelope curve was the upper limit for the stress-strain response of concrete subjected to cyclic loading;

(b) Concrete specimen subjected to cyclic loading also possessed intersection points between the loading and unloading curves of each cycle. These so called common points were located on a common point curve which was roughly parallel to the envelope curve;

(c) If the maximum cyclic stress was above the common point curve, then failure would occur after only a few load cycles.

To provide some experimental data about the response of plain concrete under general stress states, a series of multiaxial tests were carried out by Scavuzzo, Gerstle et. al. [3] on 4" cube concrete specimens subjected to arbitrary load histories. These load histories consisted of arbitrary load paths, stress reversals and reloading. Stresses were applied in steps, and the strains measured for each load step. Such tests provided important information for the construction of a comprehensive constitutive model for concrete.

In an extensive experimental study, Van Mier [4] performed tests on 4" cube specimens to study the softening behavior of concrete under uniaxial or triaxial conditions. Specimens were loaded monotonically to failure, or loading was applied with cycles to the envelope curve. Load cycles were applied with variable amplitude (in terms of stressing to the envelope in the major compressive direction). In the pre-peak region, constant deformation steps of Δl_1 = 0.15 mm were applied before loading was reversed. In the post-peak region, the slope of the descending branch was the criterion. As soon as a stress decrease $\Delta\sigma_1$ = 0.1-0.2 N/mm^2 with increasing deformation Δl_1 was observed, the loading direction was reversed. In the triaxial tests with load reversal, cyclic stress-strain behavior in the descending branch (post-peak region) was obtained.

3. Experimental Apparatus and Procedures

All tests were carried out using a 2,000 psi standard triaxial cell (see Fig. 1). It consisted of an Aluminum base plate and a steel cylinder (which were held together by steel tierods) as well as an axial piston. O-rings at appropriate locations provided proper sealing of the cell.

Test specimens were $\phi3"$ x 7.5" cylinders while f'_c was obtained from testing $\phi3"$ x 6" control cylinders. All the concrete specimens were vertically cast in batches in the laboratory and conformed to ASTM Standards C192-81 [5]. High early strength type III cement was used, and testing commenced when the specimens were seven days old. Two mix designs with nominal f'_c = 3,500 psi (type A) and 6,000 psi (type B) were used.

Two days prior to testing, specimens were removed from the water-bath to prepare for testing. Preparation included measurements of specimen diameter, application of Hydrostone caps, gluing of axial studs and radial targets (for axial and radial deformation measures respectively) onto proper locations on the specimen surface, and coating with a dual-layer leak-proof urethane jacket to isolate the specimen from the pressurized cell fluid during testing.

Two LVDTs were used to measure axial deformations. These were small ($\phi3/8"$ x 1") light weight (5 oz.) devices capable of functioning under 5,000 psi pressure. They were located diametrically opposite one another with gage length (h/2) specified along the middle half of the specimen.

For radial displacement measures, two proximity probes were used [6]. These probes were mounted directly onto the base plate of the triaxial cell and were placed diametrically opposite each other. Each probe was set up with the probe tip directed to a steel target located at mid-height of the specimen. An initial spacing of 0.040" was maintained between the probe tip and the target (It should be noted that at the time of preliminary testing, both radial probes were unavailable. Hence no radial deformations were recorded).

Confining pressure was applied by pressuring the cell fluid, an electrically non-conductive Silicone liquid, which in turn was pressurized by nitrogen gas via a gas-fluid pressure transfer. Pressure level was controlled through a pressure regulator, while cell pressure was maintained constant (± 5 psi) by a hand-operated relief valve.

Axial load was applied via a feedback controlled hydraulic powered MTS test machine (maximum capacity of 110 kips). Figure 2 shows the complete instrumentation. A detailed description of all the above can be found in Ref. 7.

Each test typically started out with the specimen mounted in the cell, followed by proper setting of the LVDTs. The steel cylinder was then lowered to the base plate and fastened. The cell was then filled with Silicone oil which was subsequently pressurized to a predetermined level which was held constant. Axial stress was then increased monotonically or cycled between preset stress levels until failure of specimen occured [8].

4. Preliminary Test Results

The initial tests (60 specimens in all) were performed with the following parameters:

(a) confining pressure at 0, 300, 600 and 1,200 psi;

(b) monotonic axial compression with time to failure at 1 minute (fast strain rate), 5 minutes (normal strain rate) or 60 minutes (slow strain rate) under various confining pressure levels;

(c) cyclic axial compression with different cyclic stress ranges (see Table 1) at each confining pressure level;

(d) different strength level concrete, type A (3,5000 psi) and type B (6,000 psi)

In the stroke controlled monotonic tests, axial load was increased at various constant strain rates until failure occurred. For confining pressure of 1,200 psi, the strain rates applied were 9.33×10^{-6} in/in/sec (slow), 1.11×10^{-4} in/in/sec (normal) and 5.56×10^{-4} in/in/sec (fast).

In the load controlled cyclic tests, specimens were subjected to different levels of maximum axial cyclic stress and stress range (specified as % of the peak stress σ_a obtained from monotonic tests with normal strain rate, under the same confining pressure level) until failure occurred. The cyclic load function was specified as Haver-sine (sine wave-form whose most negative peak was the "zero reference") with a period T = 1.5 minutes (see Table 1). A main objective for carrying out these preliminary tests was to establish the maximum and minimum stress range for carrying out the final low-cycle fatigue tests.

Results from the preliminary tests indicated that increase in confining pressure resulted in increased strength and ductility of concrete. Also, type A concrete followed the same trend as type B concrete. The lower strength concrete had a more pronounced ductility than the higher strength concrete, a phenomenon that existed both in unconfined and confined specimens.

Strain rate effect on confined concrete had the same effect as it did in unconfined concrete (see Fig. 3 (a) and (b)). At faster strain rates, the specimen attained higher strength and initial stiffness. At slower strain rates, effect of creep under high stress level led to lower strength. Also, there were difficulties in obtaining the post peak behavior in slower rate tests. This was because at peak load levels, substantial deformation caused the urethane jacket to tear open and hydraulic fluid to enter the already damaged concrete specimens. Pilot tests performed on unjacketed specimens showed both strength reduction and substantial decrease in ductility under such conditions.

Table 1 presents a summary of the cyclic test results obtained in this initial test series. As evident from Table 1, for both confined and unconfined specimens, at a given minimum stress, the number of cycles to failure decreased with increasing maximum cyclic stress level. While at a given maximum stress, the number of cycles to failure increased less sharply with increasing minumum stress level. The mimimum stress levels were chosen as 0.30 σ_a and 0.40 σ_a (corresponding to stresses induced by dead loads of structure). For maximum stress levels, stresses above 0.85 σ_a were tried. The lower limit of the maximum cyclic stress had to be increased from $0.90\sigma_a$ to $0.93\sigma_a$ at the higher confining pressure in order to ensure failure in a limited number of cycles.

Fig. 4(a) and (b) show respectively the cyclic axial load-displacement behavior of type B concrete with two different stress ranges at confining pressure = 1,200 psi. When cyclic load was first applied, large deformation resulted. With increasing number of load cycles, the subsequent hysteresis loops generally reached a stable stage (with small variation in each loop). The area bouded by the hysteresis loop would again increase right before failure occurred. Tests under smaller confining pressure typically followed the same trend.

Failure patterns for all specimens tested were of the "splitting-type" (along major compressive direction) . Surface cracks were typically located in the middle 2/3 portion of the specimens. It should be noted that crack plane may sometimes be located near or through the axial LVDT mounting stud(s) resulting in invalid axial strain data in the post-peak region of the test.

5. Conclusions

The most important results of the preliminary tests are :

(a) Concrete strength and ductility increase with an increase in confining pressure. The lower strength level concrete attained much higher ductility than the higher strength concrete;

(b) Strain rate effect on confined concrete have the same effect as they do on unconfined concrete. Higher strain rate results in higher strengths and initial stiffness, while the inverse is true for test with slower strain rate;

(c) Number of cycles to failure are very much influenced by the maximum cyclic stress level and stress differential in each cycle. For a given minimum stress, the number of cycles to failure decreases with increasing maximum stress level; while for a given maximum stress, the number of cycles to failure increases as the minimum stress level increases;

(d) When the cyclic load is first applied, large deformation results. The subsequent hysteresis loops generally reach a stable stage and the variation in the loops is quite small until the specimen is very close to failure;

(e) The cyclic stress-strain characteristics with confining pressure appears to follow an envelope curve which is very close to the respective monotonic stress-strain curve obtained from tests with normal strain rate;

(f) The use of a leak-proof jacket on fluid pressure confined specimen is important for obtaining the true response of triaxially loaded concrete.

References

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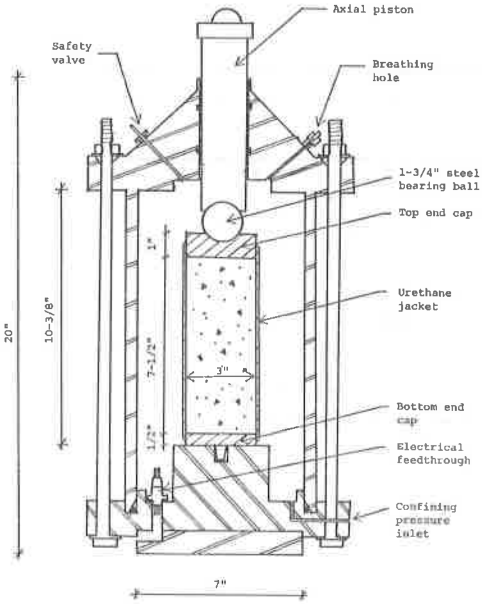


Figure 1   2,000; psi Triaxial Cell

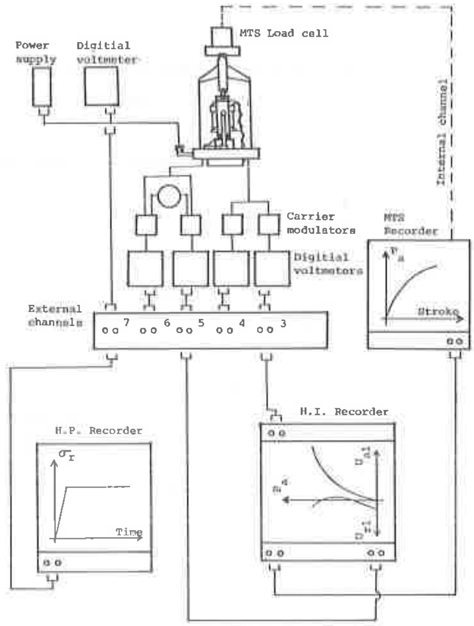


Figure 2   Set-Up of Instrumentations for 2,000 Triaxial Cell

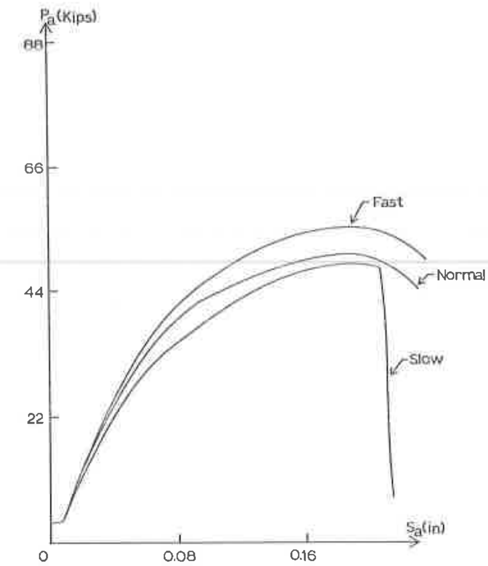


Figure 3(a) Strain Rate Effect on Type A Concrete at Confining Pressure = 1,200 psi

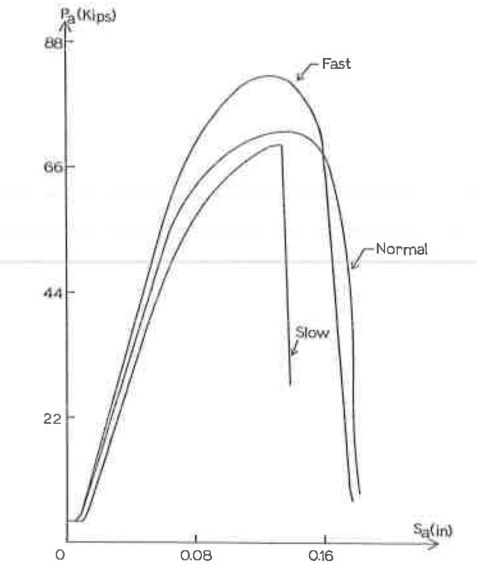
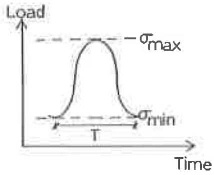


Figure 3(b) Strain Rate Effect on Type B Concrete at Confining Pressure = 1,200 psi

Table 1 Cyclic Triaxial Compression Tests Results

Confining Pressure (psi)	Type A Concrete		Type B Concrete	
	$\sigma_{max}/\sigma_{min}$ (% of σ_a)	Number of Cycles to Failure	$\sigma_{max}/\sigma_{min}$ (% of σ_a)	Number of Cycles to Failure
0	0.95/0.30	2	0.95/0.30	0
	0.85/0.30	50*	0.90/0.30	17
	0.90/0.40	39	0.95/0.35	1
300	0.88/0.30	60*	0.98/0.30	3
	0.91/0.30	40*	0.93/0.30	21
	0.91/0.30	-	0.98/0.40	4
600	0.95/0.30	10	0.95/0.30	10
	0.90/0.30	40*	0.93/0.30	23
	0.95/0.40	14	0.95/0.40	-
1,200	0.95/0.30	9	0.95/0.30	6
	0.93/0.30	31	0.93/0.30	13
	0.95/0.40	-	0.95/0.40	7

* specimen did not fail



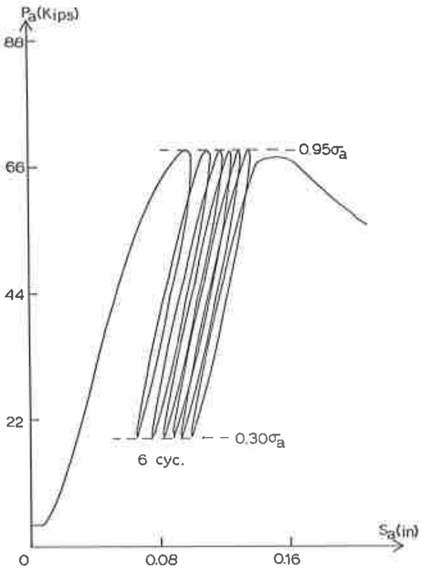


Figure 4(a) Cyclic Axial Load-Displacement Behavior of Type B Concrete at Confining Pressure = 1,200 psi (Cont'd)

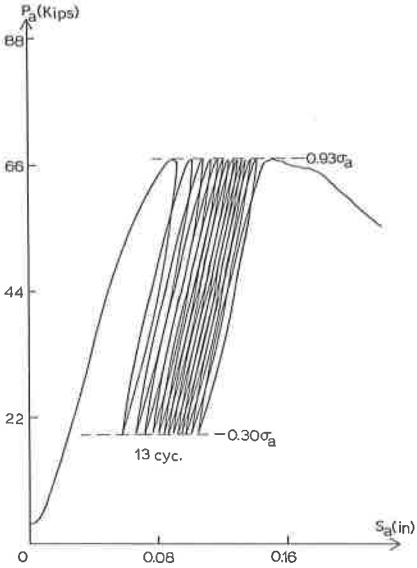


Figure 4(b) Cyclic Axial Load-Displacement Behavior of Type B Concrete at Confining Pressure = 1,200 psi