$R = \sigma_c^{min}/\sigma_c^{max}$

σ_c^{min} = lower stress limit for pulsating load

N = number of load pulses to fatigue failure

The equation is valid for tensile and compressive stresses and has validity in the region shown in FIG. 3.

THE OBJECT OF THE TESTS

The object of the tests was to investigate the validity of the hypothesis and to produce test information for these regions of the diagram in the Swedish Code of Practice BBK79 (6), FIG. 2, in which stress reversals occur. Two test series were carried out.

In the first series transversely compressed cubes with a pulsating splitting load were used. Comparison of results from specimens with only compressive load pulses with results from specimens with stress reversals was expected to give the information necessary for an estimation of the validity of the hypothesis.

In the second series concrete prisms were loaded with axial pulsating compressive loads and constant transverse splitting line loads. The intention was to find if the hypothesis can be used to determine whether fatigue failure will be tensile or compressive. The results were to be compared with the requirement in the Swedish Code of Practice BBK79 (6).

TESTS ON CONCRETE CUBES

Test arrangement

It is very difficult to fix concrete specimens satisfactorily in the machine and to load them with stresses alternating between direct tension and compression. External geometrical load eccentricities as well as internal ones due to density and stiffness variation within the specimens must be avoided. A less sensitive cube splitting test with a transverse compressive load was therefore used to obtain load pulses alternating between tension and compression. Because of limitations in the contact pressure under the line loads, it was not possible to obtain stress reversals with high compressive stresses in the amplitude. The concrete cubes were loaded according to FIG. 4 and 5.

The stress in the middle part of the cube transverse to the section through the line loads P, FIG. 6, is determined by equation (2)

$$\sigma = \frac{-Q}{a^2} + \frac{2P}{\pi a^2} \qquad \ldots (2)$$

where Q = compressive load transverse to splitting load

P = splitting load

a = side length of cube

A stress - strain relation determined at the middle of the cube transverse to the section through the line loads for a cube which is first loaded by the load Q and then by the splitting load P up to static tensile failure is shown in FIG. 7.

The pulsating line load P was obtained from an oil pulsator.

The Scope of Tests

Two cube sizes were tested - 56 cubes with side length 0.15 m (5.91 in) and 29 cubes with side length 0.20 m (7.87 in). The change to the bigger cubes was made because it was easier to apply the load precisely.

The object of the investigation was to test the validity of the hypothesis by comparing results from test series where the stress ratio was R=0 (24 tests) with test series where $R < 0$ (61 tests). If the hypothesis applies, there will be no difference between tests with the two R-values.

In the tests with both R-values the tensile stress due to the load P is superposed on the compressive stress due to load Q in order to achieve the desired upper and lower stress limits.

Test Results

The concrete had static compressive strengths in the range f_{cc} = 28-70 MPa (3-10 ksi) as determined on cubes with side length 0.15 m (5.91 in).

The analysis of the results is presented in histogram and in Wöhler-diagrams (S-N-curves).

Histograms of the ratio $\log_{10} N_m/\log_{10} N_c$, where N_m is the measured number of load pulses to fatigue failure and N_c is that calculated from equation (1) and R=0, are presented in FIG. 8. The mean values of the ratio are below 1.0 and of the same magnitude for series with R=0 and $R < 0$.

The test results are also presented in Wöhler-diagrams in

FIG. 9. It can be stated that more than half of the test points are situated around the broken line for equation (1) with R=0, with about the same dispersion as observed in fatigue tests without stress reversals, as reported in (9). The remaining tests have considerably smaller measured numbers of load cycles to failure than calculated ones.

There is no direct reason why the scatter in the results should be greater when the stresses are pulsating between tension and compression than when these are pulsating on the tensile or compressive side only. The more complex loading set up is a probable cause of the increased scatter.

Normally, when the size of the test specimens increases, the mean strength decreases and the scatter is reduced. In the test series there are cubes with side length 0.15 m (5.91 in) and 0.20 m (7.87 in). It may be that the scatter in the results will be smaller for the bigger cubes. As the fatigue strength is related to the static strength on the same cube size, there should not be any disturbance in the fatigue strength reduction level for the two cube sizes. Morover it is easier to center the loads on the bigger cubes. Therefore only the results for the bigger cubes are analysed in a histogram and a Wöhler-diagram in FIG. 10. The test results now have about the same dispersion along the broken line for equation (1) and R=0 as that obtained in the fatigue investigation, (9), with tensile stress pulses in cube splitting tests. The very diverging results which the smaller cubes gave are now almost absent. The results, interpreted in this way, suggest that the compressive stresses included in the stress amplitudes may have little influence on the fatigue of concrete. According to the submitted hypothesis, the fatigue reduction seems to be determined mainly by tensile stress pulses in the stress amplitude.

TESTS ON CONCRETE PRISMS

The Scope of Tests and Test Arrangement

The previous test series for investigation of the fatigue of concrete for stresses alternating between tension and compression were extended to include tests on prisms 0.15x0.15x0.47 m^3 (5.91x5.91x18.5 in^3). The prisms were loaded axially by a pulsating compressive load Q from a servohydraulic machine and transversally by constant splitting line loads P, according to FIG. 11. The stress variations in the splitting zone of the prism and in the upper and lower part of the prism are shown in FIG. 12.

One aim of the test series was to investigate whether the location of fatigue failure, in the splitting zone or in the upper or lower part of the prism, can be predicted using equation (1) and the hypothesis. The other aim was to compare the requirements in the Swedish Code of Practice BBK79 (6) with the test results.

Strain gages were used for indication of splitting tensile failure. The security circuit current from the servo hydraulic loading machine passed through the gages and was cut when the splitting crack tore off the gage. The machine then stopped immediately, giving the number of load cycles to failure and preserving the tensile fatigue appearance of the prism. If this had not been possible, a subsequent compressive failure may have masked the tensile failure.

The test series were divided into two groups with pulsating load levels which, according to the hypothesis, would lead to tensile fatigue failure in the first group and to compressive fatigue failure in the second group. Group 1 comprises 12 specimens and group 2, 10 specimens. In the second group, compressive failure outside the splitting zone would occur only if the compressive stress pulse in the stress amplitude in the splitting zone had almost no influence on the tensile fatigue there. The load levels and the expected number of load cycles to failure are presented in TAB. 1 and FIG. 12.

Test Results

The compressive strength of the concrete, determined on standard cubes with side length 0.15 m (5.91 in), was f_{cc} = 22 MPa (3.1 ksi). The static compressive strength and the splitting tensile strength for the concrete prisms, to which the fatigue strengths were related, were determined. The fatigue test results are presented in TAB. 2.

In group 1 there are three compressive fatigue failures among the intended tensile ones and in group 2 one tensile failure among the intended compressive ones. Obviously, the influence due to stress reversals is quite small, and it appears that eq. (1) according to the hypothesis can be used to predict the type of failure.

In TAB. 2 the measured numbers of load cycles to failure are related to the calculated ones using eq. (1). The calculations are made with R=0 for tensile failure. For compressive failure eq. (1) with the actual R-value is used. If eq. (1) and the hypothesis apply, these relations should be close to 1.0. It should be noted that for specimens with intended tensile failures the measured number of load cycles to compressive failure must be higher, and vice versa.

It can be concluded that for group 1 the mean of $\log_{10} N_m / \log_{10} N_c$ for tensile failure is below 1.0. For group 2 the mean of this ratio for compressive failure is close to 1.0 within the range which can be expected in fatigue tests. It is obvious that the fatigue of specimens with stress reversals between tension and compression is influenced by this type of loading, but not very much. However, it must be borne in mind that the precision of the applied load on the tensile side in relation to the failure load there is less than on the compressive side. This fact may contribute to the earlier failures with stress reversals, just as it was observed for the smaller cubes in the first series.

All tests in both groups with tensile failures for stress reversals are presented in a Wöhler-diagram, Fig. 13, and are situated on the unsafe side below the broken line for eq. (1) with R=0 according to the hypothesis. In the diagram the requirement in the Swedish Code of Practice BBK79 (6) for the actual stress amplitudes is also indicated and is situated on the safe side of the test results.

The compressive fatigue failure test results are presented in a Wöhler-diagram, Fig. 14, and show a usual dispersion around the broken lines for eq. (1) with R=0.09 and R=0.11. The requirements in the Swedish Code BBK79 for the actual stress amplitudes are situated on the broken lines.

In Fig. 15 the mean numbers of measured load cycles to fatigue failure are plotted in the diagram for determination of fatigue strength according to the Swedish Code of Practice BBK79 (6). It can be concluded that for load pulses with stress reversals the results are on the safe side in comparison with requirements in the code. The results relating to fatigue failure caused by compressive stress pulses are in approximate agreement with the code. The point for compressive failure at the stress level $\sigma_{ccp}^{max}/f_{ccp}$ = 0.65 is based on only three specimens with the lowest fatigue strength. The rest of the specimens at this stress level failed in tension and are "run outs" as far as compressive failure is concerned. This means that the mean value of the number of load cycles to compressive failure for this point should be higher.

The load pulses applied to the specimens in the tests are sinusoidal. A different load pulse form will of course influence the fatigue of the concrete.

CONCLUSIONS

The tests indicated that stresses alternating between tension and compression cause a slight reduction in the fatigue strength of concrete in comparison with that obtained for stress pulses with the same absolute maximum stress - static strength ratio and zero minimum stress. However, the reduction obtained may be due to difficulties in loading the specimens precisely on the tensile side of the load pulses. At present, the hypothesis presented cannot be regarded as quite safe.

The influence on the fatigue strength due to stresses alternating between tension and compression is not large enough to prevent the use of eq. (1) according to the hypothesis to predict whether fatigue failure will be tensile or compressive.

The requirements in the Swedish Code of Practice BBK79 (6) concerning stress reduction due to fatigue are on the safe side of the results obtained for stresses alternating between tension and compression.

ACKNOWLEDGEMENTS

This investigation was performed at the Division of Building Materials and Building Technology, Chalmers University of Technology, Gothenburg, and forms part of ongoing investigations of the fatigue properties of concrete. The tests reported here were sponsored by the National Swedish Council for Building Research and Chalmers University of Technology.

NOTATIONS

P	line load (splitting load)
Q	compressive load
R	$\sigma_c^{min}/\sigma_c^{max}$
N	Number of loading cycles up to fatigue failure
N_c	calculated value of N to fatigue failure
N_m	measured value of N to fatigue failure
a	side length of concrete cube
f_{cc}	cube strength of concrete
f_{ccp}	prism strength of concrete
f_{ct}	tensile strength of concrete (splitting test on cube)
f_{ctp}	tensile strength of concrete (splitting test on prism)
n	number of tests
r	regression coefficient
s	standard deviation
$\bar{x}$	mean value
ε	strain
σ	stress
σ_{cc}	compressive stress in concrete cube
σ_{ct}	tensile stress in concrete cube
σ_{ccp}	compressive stress in concrete prism
σ_{ctp}	tensile stress in concrete prism
σ_1 and σ_2	stress levels

REFERENCES

1. Murdock, J.W., Kesler, C.E.: Effect of Range of Stress on Fatigue Strength of Plain Concrete Beams. Journal of the ACI, August 1958, Vol. 30, No. 2, pp. 221-233.

2. Murdock, J.W.: A Critical Review of Research on Fatigue of Plain Concrete, University of Illinois College of Engineering, Engineering Experiment Station, Bulletin 475, Vol. 62, No. 62, Feb. 1965.

3. Clemmer, H.F.: Fatigue of Concrete. Proceedings of the American Society for Testing Materials, Vol. 22, II, 1922, pp. 408-419.

4. Hatt, W.K.: Researches in Concrete. Purdue University, Bulletin No. 24, Lafayette, Indiana, 1924, pp. 44-55.

5. Crepps, R.B.: Fatigue of Mortar. Proceedings of the American Society for Testing Materials, Vol. 23, II, 1923, pp. 329-340.

6. Bestämmelser för betongkonstruktioner, BBK79, Band 1, Konstruktion (Regulations for concrete structures, BBK79, Vol. I, Design). Statens betongkommitté, AB Svensk Byggtjänst, Stockholm 1979, p. 157.

7. Tepfers, R.: En undersökning av betongens utmattnings-hållfasthet. (An investigation of the fatigue strength of concrete). Statens råd för byggnadsforskning, rapport R 86:1978, Stockholm 1978, p. 121.

8. Tepfers, R., Kutti, T.: Fatigue Strength of Plain Ordinary and Lightweight Concrete. Journal of the ACI, May 1979/ No. 5, proceedings V. pp. 635-652.

9. Tepfers, R.: Tensile Fatigue Strength of Plain Concrete. Journal of the ACI, August 1979/No. 8, proceedings V. pp. 919-933.

10. Betonghandbok. Konstruktion (Handbook for concrete. Design) AB Svensk Byggtjänst, Stockholm 1980, pp. 62-74.

11. Aas-Jacobsen, K.: Fatigue of Concrete Beams and Columns. Trondheim, NTH Institutt for Betongkonstruksjoner, September 1979, Bulletin No. 70-1, p. 148.

TABLE 1 Stress limits in the applied load pulses

Group	Upper and lower part			Splitting zone		
	$\sigma_{ccp}^{max}/f_{ccp}$	$\sigma_{ccp}^{min}/f_{ccp}$	$\log_{10} N_c$ *) theory	$\sigma_{ctp}^{max}/f_{ctp}$	$\sigma_{ccp}^{max}/f_{ccp}$	$\log_{10} N_c$ **) theory
1	0,65	0,07	5,726	0,65	0,53	5,109
2	0,75	0,07	4,025	0,65	0,63	5,109

*) Calculated with eq. (1) and appropriate R-value
**) Calculated with eq. (1) R=0 according to the hypothesis

Group 1 comprises 12 specimens and group 2, 10 specimens.

TABLE 2 Fatigue test results

Group 1

Specimen No	Type of failure	$\log_{10}N_m$	$\log_{10}N_c$ T	$\log_{10}N_c$ C	$\log_{10}N_m/\log_{10}N_c$ T	$\log_{10}N_m/\log_{10}N_c$ C
8	T	4.857	5.109	5.726	0.951	-
10	C	4.889	-"-	-"-	> 0.957	0.854
11	T	3.820	-"-	-"-	0.748	-
13	C	4.412	-"-	-"-	> 0.864	0.771
21	T	4.331	-"-	-"-	0.848	-
28	T	4.478	-"-	-"-	0.876	-
29	T	3.556	-"-	-"-	0.696	-
30	C	5.012	-"-	-"-	> 0.981	0.875
32	T	4.273	-"-	-"-	0.836	-
33	T	3.255	-"-	-"-	0.637	-
34	T	4.252	-"-	-"-	0.832	-
35	T	2.954	-"-	-"-	0.578	-
MEAN	T + C	4.174	5.109	5.726	> 0.817	-
Standard deviation	T + C	0.654	-	-	0.128	-
MEAN	T	3.975	5.109	-	0.778	-
Standard deviation	T	0.621	-	-	0.122	-
MEAN	C	4.771	-	5.726	-	0.833

Group 2

Specimen No	Type of failure	$\log_{10}N_m$	$\log_{10}N_c$ T	$\log_{10}N_c$ C	$\log_{10}N_m/\log_{10}N_c$ T	$\log_{10}N_m/\log_{10}N_c$ C
14	C	3.756	5.109	4.025	-	0.933
15	C	3.653	-"-	-"-	-	0.908
16	C	3.322	-"-	-"-	-	0.825
17	C	3.591	-"-	-"-	-	0.892
18	C	4.116	-"-	-"-	-	1.023
19	C	4.290	-"-	-"-	-	1.066
20	C	3.875	-"-	-"-	-	0.963
36	C	3.079	-"-	-"-	-	0.765
37	C	4.147	-"-	-"-	-	1.030
38	T	3.255	-"-	-"-	0.637	> 0.809
MEAN	C + T	3.708	5.109	4.025	-	> 0.921
Standard deviation	C + T	0.408	-	-	-	0.101
MEAN	C	3.758	-	4.025	-	0.934
Standard deviation	C	0.398	-	-		0.099

T = tensile failure. C = compressive failure.
$\log_{10}N_c$ for tensile failure is calculated with eq. (1) according to the hypothesis.

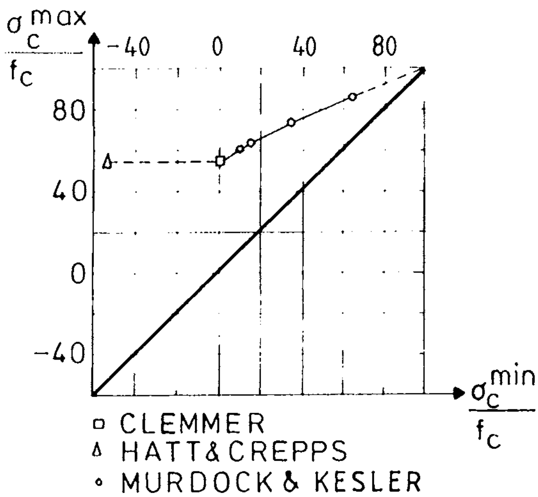

Fig. 1--Modified Goodman diagram according to Murdock & Kesler (1) for fatigue failure of concrete at 10^7 load pulses

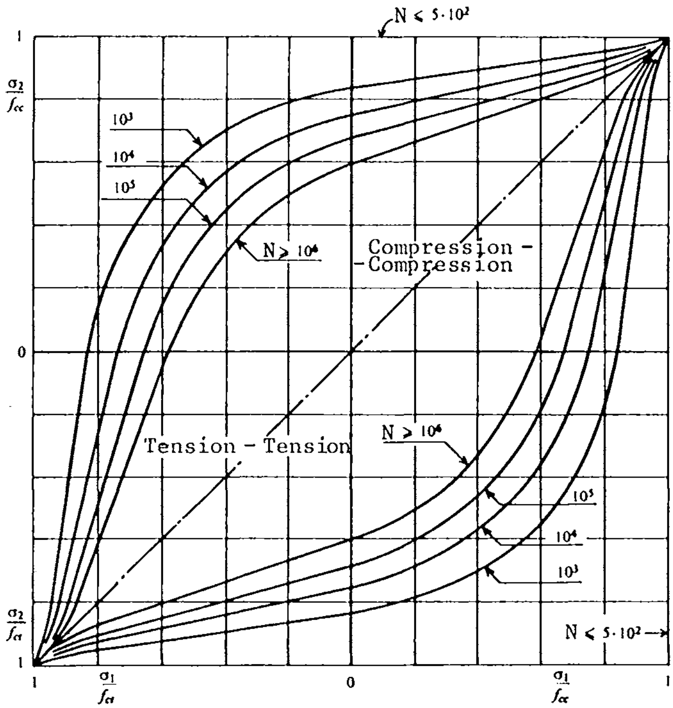

Fig. 2--Diagram for determination of the fatigue strength of concrete according to the Swedish Code of Practice BBK79, (6)