Session B 2

LOW CYCLE FATIGUE FRACTURE LIMITS OF VARIOUS KINDS OF STRUCTURAL MEMBERS SUBJECTED TO ALTERNATELY REPEATED PLASTIC BENDING UNDER AXIAL COMPRESSION AS AN EVALUATION BASIS OR DESIGN CRITERIA FOR ASEISMIC CAPACITY

By PROF. DR.-ING. MINORU YAMADA

ABSTRACT

The importances of the ductility requirements for structures and structural members against earthquake were pionted out and emphasized by professors Newmark and Hall [1]. The evaluation basis and design criteria of ductility has been applied as the ductility factor as a ratio of total deformation versus elastic deformation.[2]. The ductility factors of several real structural members had been reported [3] [13] but the definition contains practically some obscurity.

It is proposed here by the author the ductility evaluation of structural members or connections for aseismic design must be related to the repeated number of cycles and the distribution of deflection amplitudes and therefore it must be based upon the low cycle fatigue fracture limits of them subjected to alternately repeated cyclic bending with or without axial compression. So it is presented here the test results of low cycle fatigue fracture limits of various kinds of structural members, i.e. reinforced concrete, wide flange steel profil and steel pipe filled with concrete in the relation between deflection amplitudes and number of cycles until fracture with a parameter of axial load level ratios in Fig. 8.

This low cycle fatigue fracture limits relation between the deflection amplitudes and number of cycles until fracture shows a linear relation with a negative slope in log.-log. diagram with a parameter of axial load level ratios. This linear relationship shows that the low cycle fatigue fracture criteria occurs by a cumulation of some damage energy in higher order. The lower the axial load level ratios, the steeper and the larger the deflection amplitudes. From this figure it becomes possible to estimate the allowable ductility criteria in relation to the allowable distribution of deflection amplitudes and the allowable number of cycles until fracture.

Photo. 1 shows a fracture mode of a reinforced concrete test specimen under an axial load level ratio of 1/6 with a constant deflection amplitude of +30,00 mm (+0,05 Rad.) after 4 cycles. This fracture mode simulates very good to the real damaged reinforced concrete structures (Photo. 2) under strong earthquake. This good simulation shows the importances of the evaluation of ductility factor by the relationship of low cycle fatigue fracture limits.

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SYNOPSIS

Low cycle fatigue fracture tests of various kinds of structural members (i.e. reinforced concrete, wide flange steel profil and steel pipe filled with concrete) subjected to alternately repeated plastic bending under constant axial compression were carried out. The relationships between deflection amplitudes and number of cycles until fracture with the parameter of axial load level ratios were given in order to present the evaluation basis of the aseismic design criteria of structural members or connections. The low cycle fatigue fracture test specimens of these structural members were compared with the damaged structures under earthquake.

1. INTRODUCTION

The aseismic design criteria of the deformation capacities of structural members or connections have not yet been established through the sufficient experimental data. The plastic deformation capacities of them are able to be defined and have to be estimated by the relationships between deflection amplitudes and number of cycles until fracture, i.e. by the low cycle fatigue fracture limits.

Here in this paper the low cycle fatigue fracture limits of various kinds of structural members, i.e. reinforced concrete, wide flange steel profil and steel pipe filled with concrete, under various values of deflection amplitude and various values of axial compression ratio, are reported in order to present the basis of the aseismic design criteria. It is discussed here the influences of deflection amplitudes and axial load level ratios upon the hysteresis loop characteristics and the low cycle fatigue fracture limits or the number of cycles until fracture.

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The fracture modes of the low cycle fatigue test specimens subjected to constant axial compression are compared with the damaged members of real buildings under strong earthquake motion.

2. OBJECTIVES AND SCOPE

2-1. The Importances of Ductility Requirements for Structural Members or Connections for Aseismic Design

The ductility requirement for structural members or connections is the most essential problem for the practical aseismic design. It was pointed out and emphasized already by professors Newmark and Hall [1]. The lack of ductility loses the sufficient resistance of structures against the earthquake motion and caused often brittle fracture of buildings. This ductility of structural members, connections or whole structures is evaluated by the ductility factor, first introduced by professors Veletsos and Newmark [2], defined as a ratio of total deformation versus elastic deformation. Aseismicity of structures has been indicated and evaluated by this factor.

2-2. Previous Research

The previous experimental research on the ductility of structural members or connections are not yet so many. The author [3] had reported in the year 1958 on the rotation capacity of plastic hinges in reinforced concrete beams and had presented an experimental formula to calculate the rotation capacity of them with a newly introduced concept of plastic hinge range as a function of reinforcing index $pm = p\frac{\sigma_y}{\sigma_p} = \beta_1 \mu$ through the test data of 56 specimens. The higher the reinforcing index, the lower the rotation capacity, i.e. the lower the ductility factor.

On the ductility of reinforced concrete beams subjected to alternately repeated cyclic bending had been reported by the author [4]. It had been shown the existence of a linear relationship between deflection amplitudes and number of cycles until fracture in log.-log. diagram. So it was explained by the hypothesis of cumulated damage energy for low cycle fatigue fracture.

On the deformation capacity of plastic hinges in reinforced concrete columns, the author had presented the test data for one way bending under the action of constant axial compression [5] with an experimental formula for the calculation of the rotation capacity of plastic hinges. Professors Newmark and Hall [1] and Pfrang and Siess [6] had shown several test data of reinforced concrete columns under fairly lower axial load level ratios. Professor Baker and Amarakone [7] had reported test results of reinforced concrete members subjected to elasto-plastic bending under axial compression.

The low cycle fatigue behaviour and fracture limits of reinforced concrete members subjected to alternately repeated cyclic bending under the action of constant axial compression was reported by the author [8] and was shown the existence of the linear relation between deflection amplitudes and number of cycles until fracture with a parameter of axial load level ratio.in log.-log. diagram. Test result shows, the lower the axial load level ratio, the steeper the negative gradient of the line but not steeper than $-\frac{1}{2}$.

On the low cycle fatigue behaviour of steel beams had been reported by professor Popov [9], and the author [10] had presented test data of low cycle fatigue behaviour of riveted and high strength bolted joints in steel beams and had shown their peculier hysteresis loop characteristics with slipping part and bearing part. The author has clarified the cause of low cycle fracture as the cumulated damage energy of bearing part and not by total deflection amplitude or slipping part.

Recently two international symposiums, i.e. Flexural Mechanics of Reinforced Concrete, ASCE-ACI, Miami, 1964 and Effect of Repeated Loading of Materials and Structures, RILEM, Mexico, 1966, were been held to make clear the plastic behaviours of structural materials and members. At these international symposiums several valuable test data were presented.

Theoretical research on this problem were very few. The author [11] had presented an analytical approach to the elasto-plastic bending deformation of reinforced concrete members subjected to axial load with the introduction of the new concept "Limiting Strain Point". Pfrang and Siess [6] had treated the same problem with the contourlines of curvatures. For the case of alternately reversed bending of reinforced concrete members subjected to axial load had treated professor Aoyama [12] on their moment-curvature relationships with test data.

On the steel members there are yet very few research directly combining the ductility factors with stability problems. Professors Galambos and Lay [13] had treated on the necessary condition to form a plastic hinge with a sufficient yield plateau in steel beams as $\frac{l}{i_y} \leq 45$.

2-3. Definition of Ductility Factor and the Difficulties of the Experimental Determination of Ductility Factor

The ductility factor is defined as a ratio of the elastic deformation versus the total deformation [2]. This definition itself contains some theoretical obsecurity, caused from the essential differences between the elastic deformation and the plastic deformation. For instance the elastic deformation occurs with the relation to the moment distribution, however the plastic deformation occurs mainly at plastic hinge therefore concerning to the distances from the plastic hinge. (see Fig.1)

For the experimental determination of ductility factor here exist some practical difficulties. The largest difficulty is caused from the obsecurity of the end point of plastic deformation. In practical cases the plastic hinge plateau shows usually a slight negative slope after a certain up- and downward movement and there are no clear end point of this hinge plateau especially for the cases of beams without lateral buckling as shown in Fig. 2. We must therefore define the end point of the plastic hinge plateau by any method, for instance by 0,8 of yield value [13]. Another difficulity is the obsecurity of the yield value. This case occurs often in columns especially steel columns with residual stresses or in statically indeterminate structures as whole.

2-4. Low Cycle Fatigue Fracture Limit as the Scale of Ductility

As it was mentioned above, the experimental determination of ductility factor is practically very difficult from the obscurity of the end point of plastic hinge plateau or the collapse deflection.

In order to correct this obscurity the author would like to propose in this paper the low cycle fatigue fracture limit as the scale of the ductility factor. The low cycle fatigue fracture limit of alternately repeated cyclic bending is defined as the combination of number of cycles until fracture and deflection amplitudes with the parameter of axial load level ratios. In this case it is easier to define the collapse as the state, at which the member could not bear the given constant axial load, and this is very clear to observe at tosts. The clarity of the definition of collapse or the end point of plastic hinge plateau is one of the important characteristic of this proposition.

The other and the more and essential characteristic of this definition is to be able to define the ductility factor in the relation between deflection amplitude (ductility factor) and number of cycles until fracture with the parameter of axial load level ratios. The response of structures or structural members by the earthquake motion is usually alternately repeated very low cycle motion with various values of deflection amplitudes. Therefore this relationship is more essential to define the collapse of structures or structural members under earthquake motion. The deflection amplitude - number of cycles until fracture relationships with the parameters of axial load level ratios of various kinds of structural members or connections will c contribute as an endurance spectum of structural members or connections under earthquake loadings.

This relationship is proper to estimate or to evaluate the ductility factors of structural members or connections for aseismic design.

2-5. Factors Affecting on the Low Cycle Fatigue Fracture Limits

The low cycle fatigue fracture limit under alternately repeated cyclic bending is usually expressed by the relationships between deflection amplitudes and number of cycles until fracture with the parameter of constant axial load level ratios in log. - log. scale. In general this relationship is linear in log. - log. scale. The most important factor influencing upon the fracture limit is the axial load level ratio, defined as the ratio of working axial load versus the ultimate strength of centrally loaded column. The higher the axial load level ratios, the lower the deflection amplitudes and the fewer the number of cycles until fracture.

3. TESTS

3-1. Testing Method and Measuring Devices

For the alternately repeated cyclic bending fatigue test of structural members under the action of constant axial compression, a special loading frame was installed in testing machine as shown in Fig. 3. Two loading posts were combined with high strength steel bars and were set parallel to the axis of testing machine. On the inside of them there were supporting rollers at the both ends and the loading oil jack with a electric load cell at the center of them. The axial compression was applied by main testing machine through roller head installed in the cross head of testing machine and maintained carefully at a constant load level. The fracture is very clearly observed by the falling down of axial resistance.

Measuring frame was installed in the test specimen fixed at the top end and free to axial movement at the bottom end between supporting points and the total shrinkage between these points was measured too. Measuring was carried out by 1/100 mm dial gauges installed in this measuring frame. Wire strain gauges were used often upon the surfaces of the test specimens if they were necessary.

Test spans were 70 cm x 2 with central loading. Tests were controlled mainly by the center deflection amplitudes.

3-2. Test Groups and Test Series

Tests were carried out for the following three groups:
(a) reinforced concrete members, (RC)
(b) wide flange steel profil members, (H)
(c) steel pipe filled with concrete. (PC)
These three were typical structural members with two opposite behaviours, i.e. with ductile or brittle nature. Reinforced concrete member will show the typical behaviour of brittle materials and wide flange steel profil will show the typical behaviour of ductile materials.

(a) reinforced concrete members (see Fig. 4(a)),
Test specimens of reinforced concrete members had a square cross section of 16 cm x 16 cm with 4-ø13 (p =2,08%) longitudinal reinforcing steels (round bars) and a length of 160 cm (70 cm x 2 spans) reinforced with ø6 mm hoop reinforcement with 8 cm spacings. The concrete strength were =281 kg/cm or =251 kg/cm for compression and =24,6 kg/cm or =22,8 kg/cm for tension. The steel yield point of longitudinal reinforcement was =2900 kg/cm. This group was tested in three series for various axial load level ratios of N , N and N . Each series were divided into severel various deflection amplitudes from +3,20 mm to +24,00 mm.

(b) wide flange steel profil members (see Fig. 4(b)),
Test specimens of wide flange steel profil members had a cross section of equal width and depth of 125 mm x 125 mm with a flange thickness of 9 mm and a web thickness of 6,5 mm and a length of 154 cm (70 cm x 2 spans). The test specimens were rolled wide flange profil of the ordinary structural steel with a yield stress of =2670 kg/cm and a

maximum strength of =4400 kg/cm. Tests were carried out in four series for axial load level ratios of N , N , N , N .

(c) steel pipe filled with concrete (see Fig. 4(c)),

Specimens of steel pipe filled with concrete had a diameter of 139,8 mm steel pipe with a wall thickness of 4,5 mm and a length of 160 cm (70 cm x 2 spans) filled with concrete. The test specimens were electric welded steel pipe of the structural steel with a yield stress of *=4300 kg/cm and avarage* compressive strength of filled concrete was =300 kg/cm. For the loading point and supporting points for transverse load P were used the half circle loading ribbs to transmit smooth the tranverse force into the test specimen.

Each group was tested on the two main factors:

(i) test series to study on the influences of axial load level ratios upon the low cycle fatigue fracture limits. In this test usually for the cases under 0N , N , N , (N), N , where N is the ultimate strength of centrally loaded columns.

(ii) test specimens to study on the influences of deflection amplitudes upon the number of cycles until fracture under each *constant* axial load level ratio.

3-3. Test Results

Several hysteresis loop characteristics of these structural members are shown in Figs. 5, 6, 7 (in this paper for the same axial load level ratio of 1/3 for comparison) and their fracture modes are shown in Photo. 1.

(a) *reinforced concrete members*,

The hysteresis loop characteristics of reinforced concrete members were strongly influenced by the axial load level ratios and deflection amplitudes (see Fig. 5(a),(b)). Under lower axial load level ratio it occurs often slipping at loading reversal especially in the cases of beams and under medium axial load level ratios it does not occur.

The fracture modes of reinforced concrete members were as follows: Under higher axial load level ratio (N = N) with the increase of the number of repetition cycles the damaged region of concrete expanded fairly large in longitudinal direction and after a little spalling down of surface concrete occured the collapse of the member. Under medium axial load level ratio (N = N) expanded the plastic range from surface into inside and from loading point to longitudinal direction and finally it falled down by the buckling of the longitudinal reinforcements. Under lower axial load level ratio (N = N), in spite of the exposure and plastic buckling of longitudinal reinforcement, it beared more and more loading cycles but finally by the extreme buckling deformation of longitudinal reinforcement it had falled down.(see Photo. 1).

(b) *wide flange* steel profil members,

The hysteresis loop characteristics of wide flange steel profil members were strongly influenced by the axial load level ratios and deflection amplitudes (see Fig. 6(a),(b)). In several cycles at the initial stage the width of hysteresis loop became narrower, the pseudo elastic range expanded tc both positive and negative resistance sides and so the transverse resistance became stronger. Then after several cycles the hysteresis loop became stabil.

With the increase of the number of cycles the cumulation of strains in the longitudinal direction increased and the plastic or yielded range expanded in longitudinal directions. The local buckling wave of flanges occured and with the increase of the number of cycles transmitted inlongitudinal direction. Then the flange local buckling caused the local buckling of the web. This caused finally the torsion of member around the member axis and then the resistance of the member was lost.

(c) steel pipe filled with concrete,

The hysteresis loop characteristics are shown in Fig. 7(a),(b).

The fracture modes aere: At first the compression side pipe wall neighbouring to the loading point buckled and was crumpled. This crumple was not smoothed evennat the tensile side by the alternation of loading and increased their numbers. According to the increase of the number of cycles the height of the buckled crumples of pipe wall increased and the width of them became narrower. Finally the extreme outside of the crumple was cracked and splitted in longitudinal direction of the pipe by hoop tensile forces. After more several cycles the filled concrete gradually falled down from the crack openings and the lateral resistances were lost gradually.

All the test results of these three groups on the low cycle fatigue fracture limits are plotted in the relation between deflection amplitudes in the ordinate and the number of cycles until fracture in the abscissa in log.-log. scale in Fig. 8.

4. DISCUSSIONS

4-1. Fracture Criteria and Ductility Estimation

The ductility requirement of the structural members or connections is the most important factor of the aseismic capacity of structures. This ductility requirement is defined and expressed by the ductility factor = The ductility factor has been used as the evaluation basis of aseismic design and it is very convenient for the application to the design. However this definition contains some obscurities in theoretical as well as experimental meanings as it was mentioned already in 2-3. For the practical purpose it must be measured and confirmed by experiments but it is very uncertain especially for the case of beams.

On the contrary the low cycle fatigue fracture limit, especially under the action of axial compression, is tobe able to define clearly as the loss of axial resistance. This is one of the reason to define the ductility factor by the low cycle fatigue fracture limits. One of the other and the more essential reason is to become clear by the low cycle fatigue fracture limit the ductility factor in relation with the number of cycles until fracture. The response of structures and their design criteria must be estimated from such a viewpoint.

So the author would like to propose here to define the ductility factor, including the relationships between deflection amplitudes and endurance number of cycles, by the low cycle fatigue fracture limits. This method is more reasonable in theoretical as well as practical point of view.

The low cycle fatigue fracture limits therefore the ductility factors of structural members are strongly influenced by the axial compression. The higher the axial load level ratios, the lower the endurance limits, i.e. the smaller the deflection amplitudes and the fewer the number of cycles until fracture. The relationships between the deflection amplitudes and the number of cycles until fracture have, in almost all the cases, a straight line with negative slope in log.-log. scale as shown in Fig. 8, therefore:

$$N \quad = C \text{ (constant)},$$

where N : number of cycles until fracture,
: deflection amplitude,
n : constant.

The exponent n is nearly 2 for wide flange steel profil and steel pipe filled with concrete and reinforced concrete beams but larger than 2 for reinforced concrete columns almost proportional to the axial load level ratios.

4-2. Comparison between Test Result and Damaged Structures under strong Earthquake.

Photo. 1. shows an example of the low cycle fatigue fracture mode of a reinforced concrete columns subjected to a constant axial load level ratio of 1/6 with a constant deflection amplitude of = +30,00 mm after 4 cycles. The longitudinal reinforcements were exposed and buckled. The concrete was falled down inthe region of the depth of the column in longitudinal direction.

Photo. 2. shows an example of the damaged reinforced concrete column of the Hachinohe City Library, Hachinohe/Japan, by the earthquake on the 16 th. May 1968 in Japan. The longitudinal reinforcements were exposed and buckled at the top and the bottom of the column at the maximum moment section. The concrete was falled down inthe region of the depth of the column in longitudinal direction.

These two photographs show a very good similarity. Therefore the the low cycle fatigue fracture tests of structural members subjected to constant axial compression simulate fairly good with the damaged structures under strong earthquake. So it must be recognized the importances of ductility evaluation by the low cycle fatigue fracture limits.

To make clear the ductility factors of various kinds of structural members the low cycle fatigue fracture limits under the relationship with the endurance number of cycles and deflection amplitudes with the parameter of axial load level ratios is proposed as the ductility evaluation basis as an endurance spectrum of structural members for earthquakes.
The alternately repeated bending low cycle fracture limit under the action of axial compression is expressed as a relation ship between deflection amplitude and number of cycles until fracture by a straight line with a negative slope in log.-log. scale with a parameter of axial load level ratios.

Fig. 8. is the test resuots of reinforced concrete, wide flange steel profil and steel pipe filled with concrete under various axial load level ratios. From this figure it becomes possible to estimate the ductility factor of various kinds of structural members in relation to endurance. limits of cycles and acial load level ratios.

Photo. 1 and Photo. 2 show the alternately repeated low cycle fracture mode of a reinforced concrete column test specimen and damaged structure under strong earthqeake motion. The simulation of this test was very good and the fact of this good coincidence between tests and real cases shows the importances of the evaluation of ductility factor by the relationship of low cycle fracture limits.

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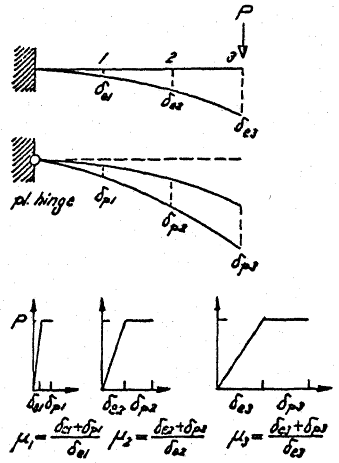


Fig. 1. Ductility Factors at various Points.

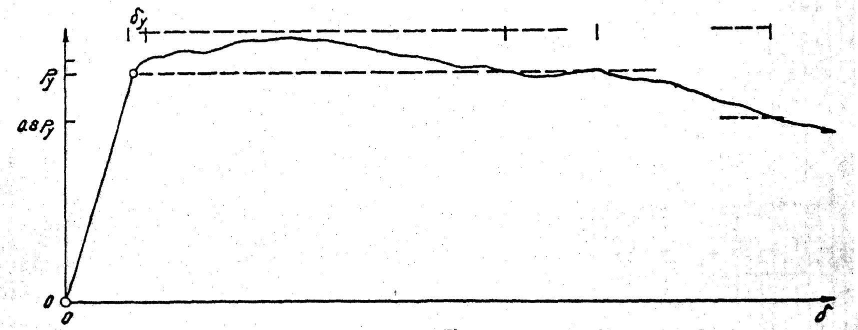


Fig. 2. Plastic Hinge Plateau and The Definitions of Ductility Factor

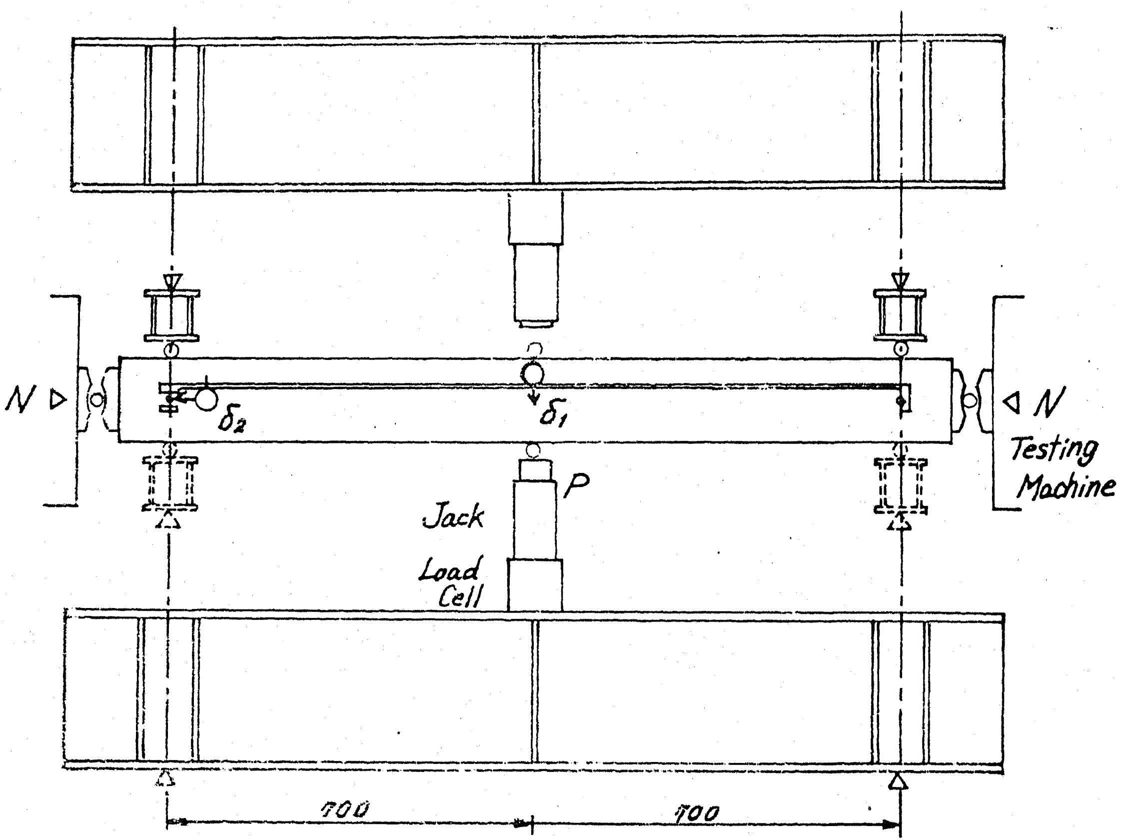
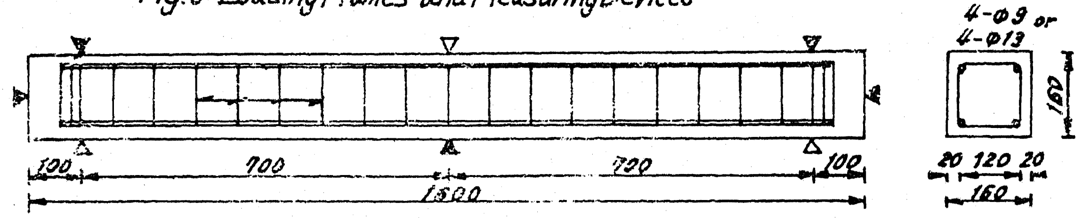
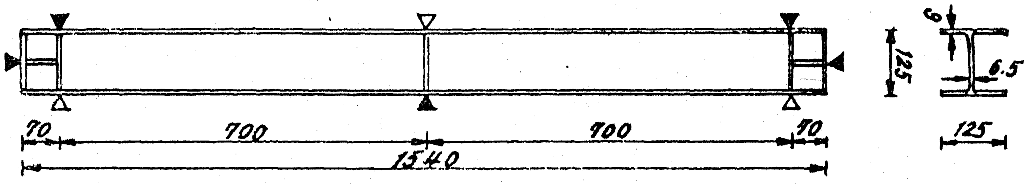


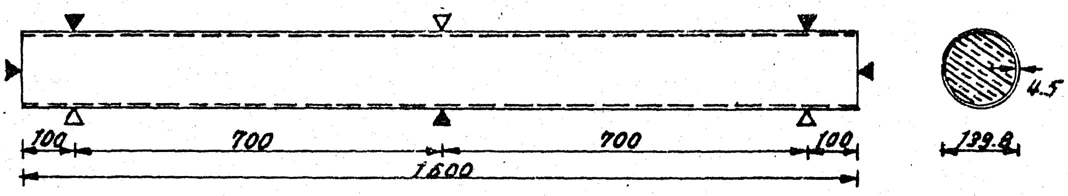
Fig.3 Loading Frames and Measuring Devices



(a) Reinforced Concrete



(b) Wide Flange Steel Profil



(c) Steel Pipe filled with Concrete

Fig.4 Test Specimens (in mm)

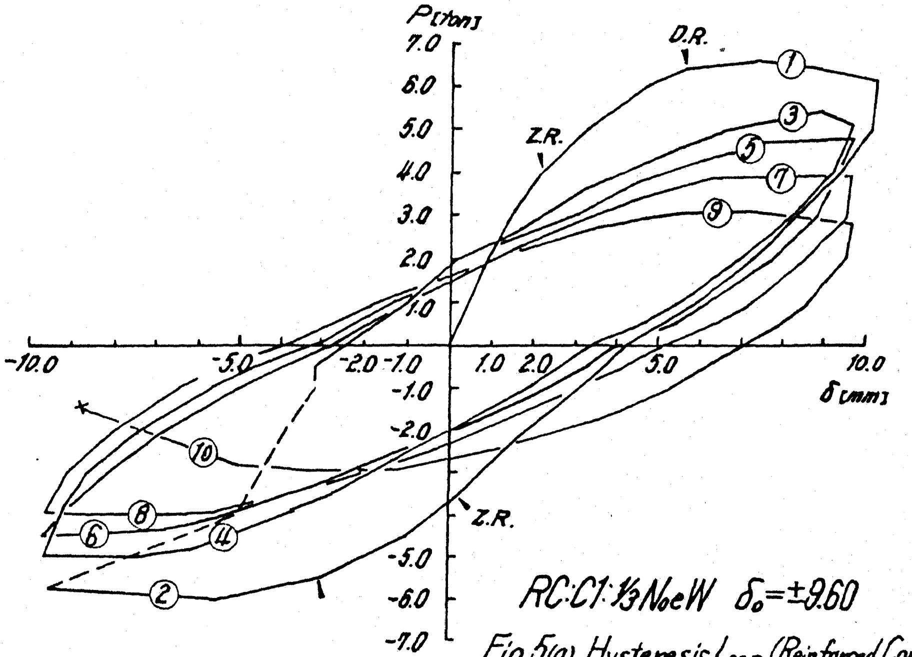


Fig.5(a) Hysteresis Loop (Reinforced Concrete)

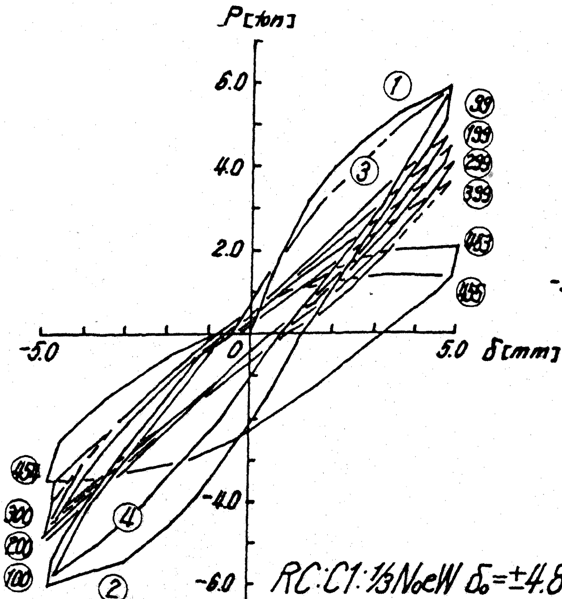


Fig.5(b) Hysteresis Loop (Reinforced Concrete)

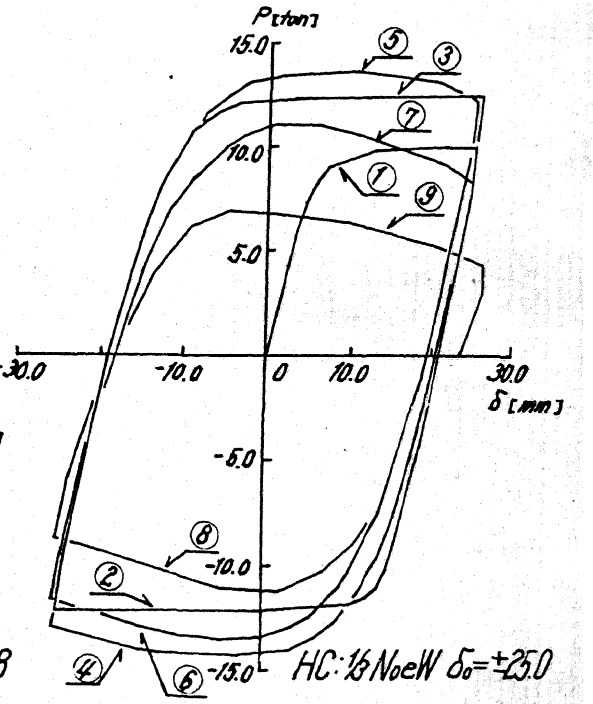


Fig.6(a) Hysteresis Loop (Wide Flange Steel Profil)

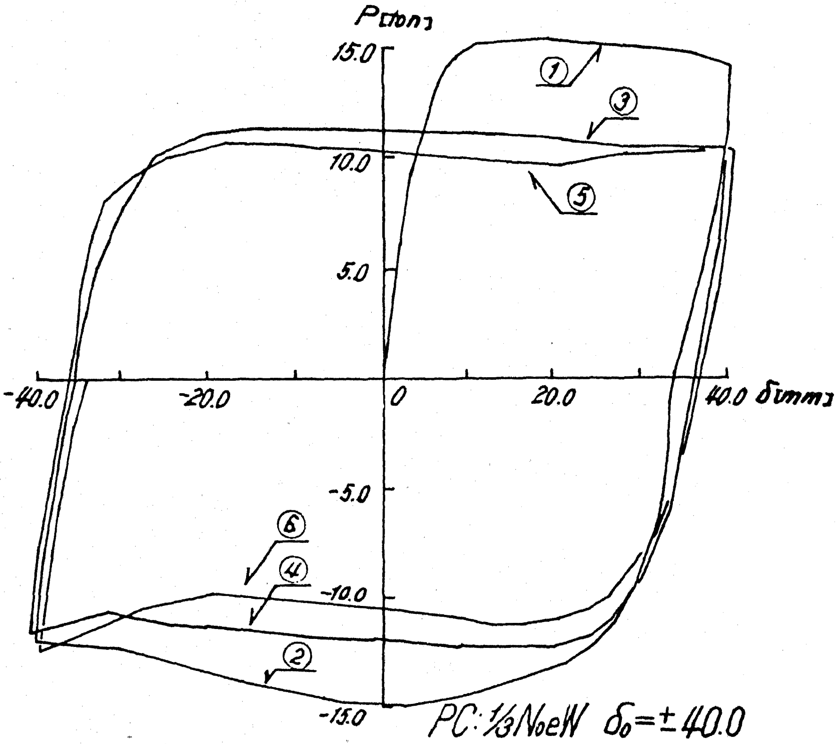


Fig. 7(a) Hysteresis Loop (Steel Pipe filled with Concrete)

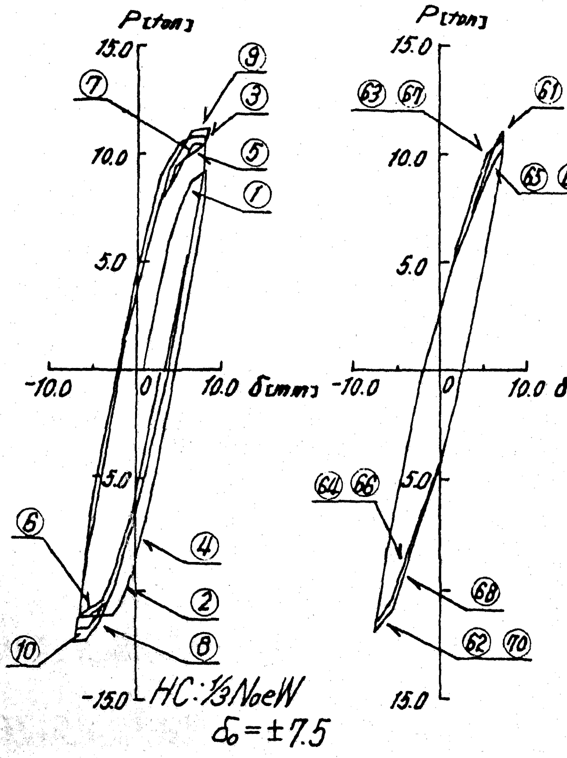


Fig. 6(b) Hysteresis Loop (Wide Flange Steel Profil)

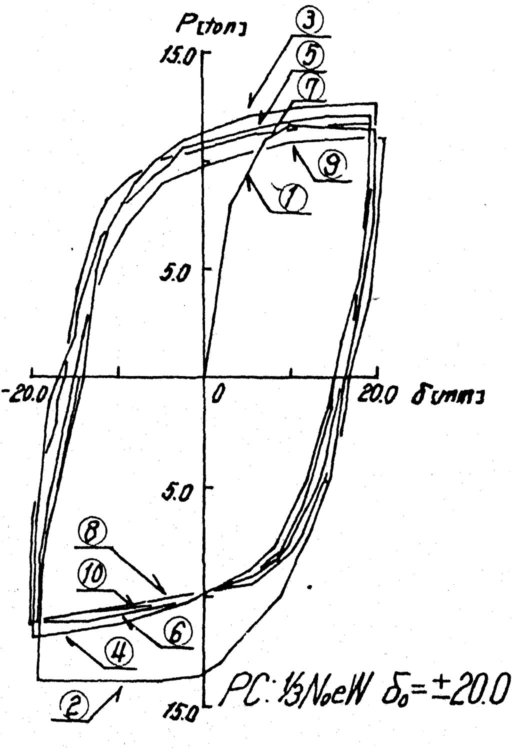


Fig. 7(b) Hysteresis Loop (Steel Pipe filled with Concrete).

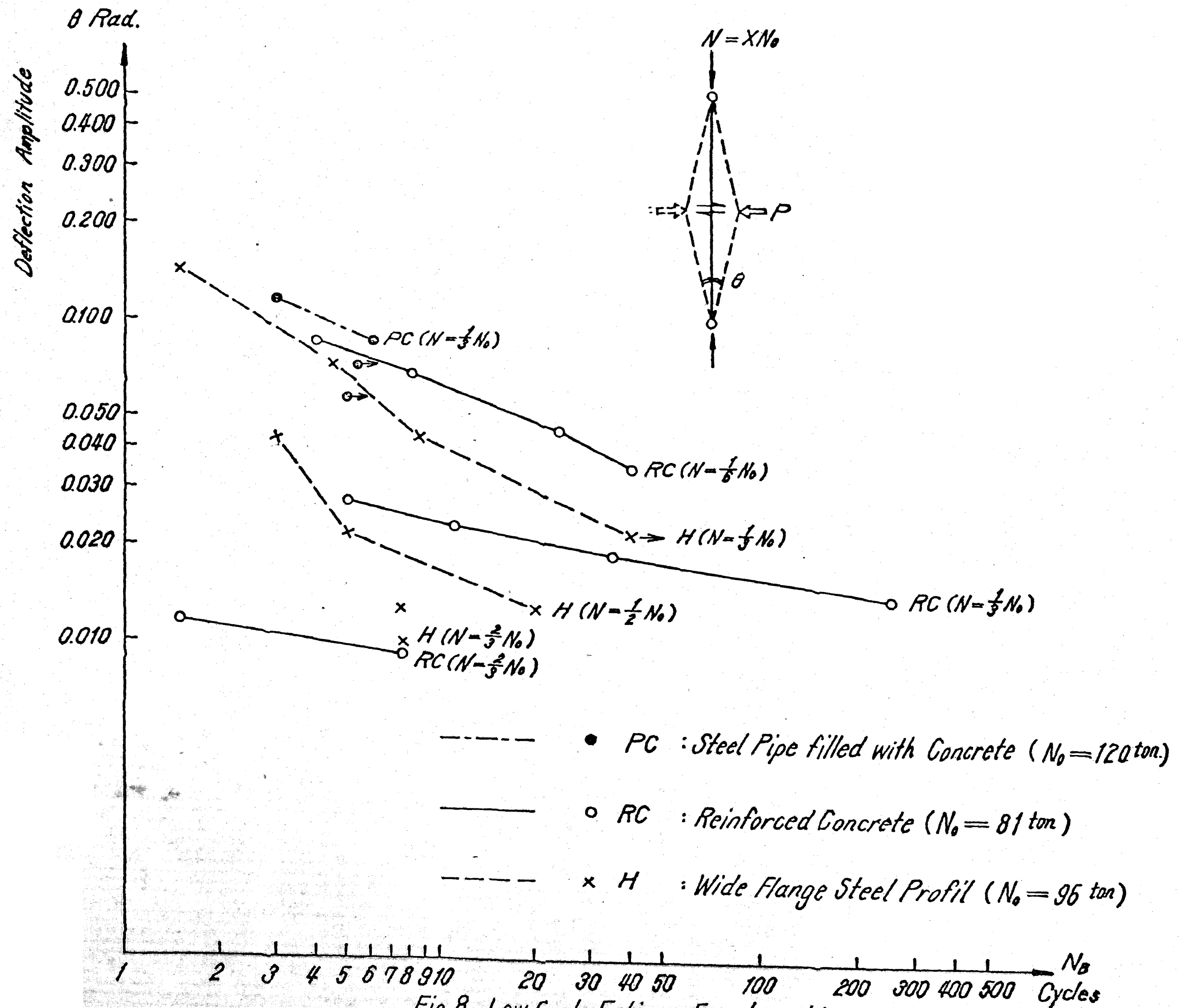


Fig. 8. Low Cycle Fatigue Fracture Limits.