539.43.011.2 : 539.389 : 539.422

Fracture Types in Load-Controlled Low-Cycle Fatigue*

By Masaki WATANABE**, Hiroshi MATSUNO***, Shigehiko YOSHIMURA***,
and Taro OKAMOTO***

It has been stated by P. P. Benham et al. that there are two types of fractures under load-controlled low-cycle fatigue test—fatigue fracture-type and necked-out fracture-type. In this report, the third fracture-type is added as an intermediate type between the fracture types above-mentioned, and discussions on the mechanism for such three types of fractures are made.

1. Introduction

Recently steel structures are used under severe service-conditions for industrial demands. As a result, the problem of the failure called "Low-Cycle Fatigue", in which the greater part of cyclic strain is plastic and the number of cycles to failure is less than 10^5 , has been receiving great attention, and so an increasing amount of information on the low-cycle fatigue behaviours of steels has been published during the past two decades.

So far, experimentation aimed at a basic understanding of low-cycle fatigue has been carried out mainly by controlling the strain rather than the load. However, practical structures in use are exposed to complicated service-conditions. They are not always subject to constant strain-cycling, or rather it matches the actual condition to consider that they are subject to load-cycling. Therefore it is industrially important to gain acquaintance with fatigue behaviors under load-cycling⁽¹⁾.

It has been stated by P. P. Benham⁽²⁾⁽³⁾ and others⁽⁴⁾ that two different types of fractures are observed in load-controlled low-cycle fatigue tests—conventional fatigue fracture-type and necked-out fracture-type following a remarkable local shrinkage. It is thought that it depends upon cyclic stress conditions⁽⁴⁾ as well as kinds of materials which type of fracture occurs⁽³⁾. However, the transitional condition between two types of fracture is not clear.

In the present paper, a study was reported on the transitional phenomenon in the types of fractures observed in load-controlled tests, especially caused by the effect of mean stress.

2. Experimental procedure

2.1 Material and specimens

SM 50 as-rolled steel was used in this test program. The chemical properties of this material are listed in Table 1. All specimens were machined from a 35 mm thick plate with the specimen-axes parallel to the rolling direction of the plate.

Hour-glass type specimens, as shown in Fig. 1, were used in order to confine fracture-locations within small regions at mid-length of specimens. The stress concentration factor of these specimens is 1.05. The results of static tensile test on these specimens are summarized in Table 2.

2.2 Description of tests

Load-controlled cycling tests were conducted at arbitrary constant stress-amplitude σ_a under mean stresses $\sigma_m = 0, 6, 8, 11, 16$, and 24 kg/mm^2 . In these tests, maximum stresses $\sigma_{\max} (= \sigma_m + \sigma_a)$ above yielding stress σ_Y were applied so that the number of

Table 1 Chemical composition and mechanical properties of tested material

Chemical composition (wt %)					
C	Si	Mn	P	S	
0.16	0.41	1.35	0.021	0.010	
Mechanical properties					
Yield-ing stress kg/mm ²	Tensile strength kg/mm ²	Elonga-tion G.L. = 80mm %	Reduc-tion of area %	True fracture stress kg/mm ²	True fracture strain
38.1	58.1	35.0	68.1	123.1	1.146

Table 2 Results of static tensile test of hour-glass type specimen

Yielding stress kg/mm ²	Tensile strength kg/mm ²	Reduction of area %	True fracture stress kg/mm ²	True fracture strain
39.1	60.0	66.8	124.7	1.096

* Received 11th January, 1971.

** Professor, Faculty of Engineering, Osaka University.

*** Graduate Course, Osaka University, Suita.

cycles to failure might be within the range of low-cycle fatigue ($N_f < 10^5$). The axial-load type fatigue machine was used at the frequency of about 10 c/min with a cyclic load of sine wave.

For the purpose of investigating the changes in the shapes of specimens, their profiles were photographed at intervals during test, and minimum diameters and radii of curvature at the tested part of specimens were measured.

The surface at the tested part of each specimen was inspected with a magnifying glass ($\times 10$) and the number of cycles at which fatigue cracks were discerned for the first time was recorded.

A special detector, which is shown in Fig. 2, was mounted at the minimum section of the specimen in order to measure the change of its diameter during test. Figure 3 shows details of the method, how the electrical output of the detector and that of the load-cell of the fatigue machine were recorded with an X-Y recorder as "Load-diametral displacement hysteresis curves".

Fig. 1 Dimensions of hour-glass type specimen

Fig. 2 Details of diametral displacement detector

Fig. 3 Method recording load-diametral displacement hysteresis curve

3. Results and discussion

3.1 Relation between cyclic stress and fracture-type

The stress amplitude-number of cycles to failure diagrams (σ_a - N_f diagrams) are shown in Fig. 4. As seen from this figure, σ_a - N_f diagram for each mean stress is approximated to a straight-line relationship in log-log scale, and, as mean stress increases, σ_a - N_f diagram shifts to the side which indicates a decrease in the number of cycles to failure.

Now, from the observation of tested specimens after failure (details of this observation will be stated in the next paragraph), the types of fracture are classified into three as follows; conventional fatigue fracture (called "Fatigue fracture-type"), necked-out type fracture following a remarkable local shrinkage (called "Necked-out fracture-type"), and, as an intermediate type between these, fatigue type

Fig. 4 Stress amplitude σ_a -number of cycles to failure N_f diagrams

Fig. 5 Relation between cyclic stress condition σ_m , σ_a and fracture-type

Fig. 6 Profiles of specimen during test, shape after failure and appearances of fracture-surface for fatigue fracture-type
 $(\sigma_m = 11 \text{ kg/mm}^2, \sigma_a = 30 \text{ kg/mm}^2; N_c = 6500, N_f = 7179)$

Fig. 7 Profiles of specimen during test, shape after failure and appearances of fracture-surface for necked-out fracture-type
 $(\sigma_m = 11 \text{ kg/mm}^2, \sigma_a = 36 \text{ kg/mm}^2; N_f = 52)$

fracture following some local shrinkage (called "Intermediate fracture-type"). In Fig. 4, the type of fracture for each specimen is distinguished with a mark. As shown in this figure, most specimens suffer fatigue type fracture at mean stress $\sigma_m = 0 \text{ kg/mm}^2$, but, as mean stress increases, intermediate type and necked-out type fractures come to occur.

In order to know clearly the relation between cyclic stresses and the types of fracture, the experimental results are arranged in the manner devised by Goodman as shown in Fig. 5. In this figure, dot-dash-lines show the relations between mean stress and stress amplitude which indicate equal number of cycles to failure, respectively. Then the marks which represent the types of fracture are the same as in Fig. 4. Straight lines PQ and P'Q' show that cyclic maximum stresses $\sigma_{\max}(=\sigma_m + \sigma_a)$ are equal to the tensile strength σ_B and the yielding stress σ_Y listed in Table 2, respectively. The experimental results in this study are plotted within the range between these straight lines, and, moreover this range is divided into three regions in accordance with the types of fracture—fatigue fracture-type region, intermediate fracture-type region and necked-out fracture-type region (transitional boundaries of these regions are indicated with broken lines AB and CD). It is interesting, as it is clear from this figure, that necked-

out type fracture is able to occur under cyclic load, even though maximum stress $\sigma_{\max}$ does not equal the tensile strength σ_B .

Fig. 9 Relation between cyclic stress condition σ_m , σ_a and reduction of area ϕ

(a) Profiles of specimen during test

(b) Shape after failure

(c) Appearance of fracture surface

Fig. 8 Profiles of specimen during test, shape after failure and appearances of fracture-surface for intermediate fracture-type

($\sigma_m = 11 \text{ kg/mm}^2$, $\sigma_a = 33 \text{ kg/mm}^2$, $N_c = 1207$, $N_f = 1286$)

3.2 Change of shape during load cycling and appearance of fracture

The profiles at intervals during test, the shapes after failure and the appearances of fracture-surface of typical specimens are shown in Figs. 6, 7 and 8, which show the cases of fatigue fracture-type, necked-out fracture-type and intermediate fracture-type, respectively.

In the case of the specimen shown in Fig. 6, fatigue cracks are detected on the surface of the tested part of the specimen at the number of cycles $N_c = 6\,500$ and fatigue fracture occurs finally at the number

of cycles $N_f = 7\,179$. No dimensional change in the profiles of the specimen can be observed, at least, until fatigue cracks are detected. In Fig. 6(c), a silvery part is perceptible in the fracture surface. This shows that fatigue cracks propagate gradually through this part, which has been termed "Fatigue fracture surface". Moreover, a gray part in the fracture surface shows a surface that has been termed "Final fracture surface".

As it is clear from Fig. 7(a), local shrinkage occurs during load-cycling and it develops gradually as the number of cycles increases, until this specimen

(F: Fatigue fracture-type, I: Intermediate fracture-type, N: Necked-out fracture-type)

Fig. 10 Changes of shapes of specimens during test

fractures finally in the shape of "Cup and cone" as in Fig. 7(b). As a result, the reduction area of the tested section was measured to be 66% after failure, and this value is approximately equal to that obtained in the static tensile test.

An example of an intermediate type fracture is shown in Fig. 8. Though a local shrinkage occurs during load-cycling and it develops gradually in subsequent cycles [as shown in Fig. 8(a)], fatigue cracks can be detected on the surface of the tested part of the specimen at the number of cycles $N_c=1\,207$ and finally lead to fracture at the number of cycles $N_f=1\,286$ in accordance with both effects of local shrinkage and fatigue-cracks. The shape after failure and the appearances of the fracture surface are shown in Fig. 8(b) and (c).

In Fig. 9, dot-dash-lines indicate the relations between mean stress and stress amplitude which give equal values of the reduction of area φ instead of equal number of cycles to failure N_f in Fig. 5. As shown in this figure, the reduction of area φ is less than 40% in specimens which suffered fatigue type fracture. On the other hand, in specimens which suffered necked-out type fracture, the value ranges from 60% to 69%. Therefore, it is found that the types of fracture caused by load-cycling have correlation to the reduction of area after failure.

In order to discuss geometrical behaviors of tested specimens subjected to cyclic load, the changes in the ratios λ of the radius $d/2$ of minimum section to the radius ρ of curvature of specimens ($\lambda=d/2\rho$)* are investigated at intervals during tests from photographs of the profiles of specimens, as shown in Fig. 10. In the figure, the relations between the ratio of number of cycles to that of cycles to failure N/N_f and the ratio of λ to λ_0 for the initial shape of the specimen $m(=\lambda/\lambda_0)$ are plotted. The specimens, which show fatigue fracture-type, maintain an approximately

Fig. 11 One example of load-diametral displacement hysteresis curves for $\sigma_m=0\text{ kg/mm}^2$ ($\sigma_a=40\text{ kg/mm}^2$, $N_f=3\,282$)

* Index of λ , which represents the shape of specimen, has often been used in elasto-plastic stress analyses of round bars with circular notches^{(5) (6)}. Also, it has been used in discussing the changes in the shapes of specimens in strain-controlled low-cycle fatigue tests⁽⁷⁾.

constant value of m over the most part of cycles to failure. However, in the cases of specimens which suffered necked-out type fracture, the value of m begins to increase gradually after certain load-cycles and increases rapidly just before failure. In the cases of intermediate fracture-type, the relations between N/N_f and m are about the same as in the cases of necked-out fracture-type, and, as shown in the figure, fatigue cracks are detected after the value of m begins to increase.

3.3 Relation between load-diametral displacement hysteresis curves and fracture-types

The examples of load-diametral displacement hysteresis curves in initial, stationary and final stages are shown in Figs. 11 and 12 for mean stresses $\sigma_m=0\text{ kg/mm}^2$ and 11 kg/mm^2 (fatigue fracture-type, intermediate fracture-type and necked-out fracture-type).

Generally speaking, hysteresis curves shift gradually in stationary stage, and remarkably in initial and final stages, in the direction which represents that diametral displacement increases (the diameter of a specimen decreases). Such a phenomenon is well-known as "Cyclic creep".⁽³⁾ However, as shown in Fig. 11, hysteresis curves shift in the reversed direction in initial stage at mean stress $\sigma_m=0\text{ kg/mm}^2$.

Moreover, it should be noted from the hysteresis curves for the stationary stage that almost closed

(a) One example of fatigue fracture-type ($\sigma_a=30\text{ kg/mm}^2$, $N_f=7179$)

(b) One example of intermediate fracture-type ($\sigma_a=33\text{ kg/mm}^2$, $N_f=1286$)

(c) One example of necked-out fracture-type ($\sigma_a=36\text{ kg/mm}^2$, $N_f=54$)

Fig. 12 Examples of load-diametral displacement hysteresis curves for $\sigma_m=11\text{ kg/mm}^2$

hysteresis curves are formed in the cases of fatigue fracture-type at both $\sigma_m = 0 \text{ kg/mm}^2$ and $\sigma_m = 11 \text{ kg/mm}^2$, and that closed hysteresis curves are not formed in the cases of intermediate fracture-type and necked-out fracture-type.

To clarify the details of stress-strain hysteresis behaviors, changes in the diametral tensile and compressive strain ranges ($\Delta\epsilon_{dt}$ and $\Delta\epsilon_{dc}$) defined in Fig. 13, and also the maximum and minimum diametral strains ($\epsilon_{d\max}$ and $\epsilon_{d\min}$) are plotted in Fig. 13(a) and (b) corresponding to Fig. 12. As it is found

(a) Change of max and min diametral strain $\epsilon_{d\max}$, $\epsilon_{d\min}$

(b) Change of tensile and compressive diametral strain ranges $\Delta\epsilon_{dt}$, $\Delta\epsilon_{dc}$

Fig. 13 Change of max. and min. diametral strain $\epsilon_{d\max}$, $\epsilon_{d\min}$ and tensile and compressive diametral strain ranges $\Delta\epsilon_{dt}$, $\Delta\epsilon_{dc}$

from Fig. 13(a), in the cases of fatigue fracture-type, both of the strain ranges are approximately constant in the greater part of cycles except initial and final cycles, and then they are nearly equal to one another. On the other hand, in the cases of intermediate fracture-type and necked-out fracture-type, $\Delta\epsilon_{dt}$ is constant approximately in stationary cycles but thereafter increases gradually until it increases rapidly in final cycles. On the other hand, $\Delta\epsilon_{dc}$ maintains constant value approximately and increases slightly in final cycles. Then $\Delta\epsilon_{dt}$ is always larger than $\Delta\epsilon_{dc}$.

So, taking note of the above fact, the relations

Fig. 14 Relation between cyclic stress condition σ_m , σ_a and strain range ratio r

Fig. 15 Relation between strain range ratio r and reduction of area ϕ

between the types of fracture and the strain range ratio $r(=\Delta\epsilon_{de}/\Delta\epsilon_{dt})$ are investigated in stationary cycles in which both strain ranges are about constant respectively, and the results are shown in Fig. 14. In this figure, dot-dash-lines indicate the relations between mean stress and stress amplitude which give equal values of the strain range ratio r , respectively, instead of equal reduction of area in Fig. 9. It is found from the figure that the strain range ratios r are almost close to -1.0 for fatigue fracture-type, are more than -0.9 for necked-out fracture-type, and take values from -0.9 to -1.0 for intermediate

fracture-type. From Fig. 14 and Fig. 9, the correlation between strain range ratio r and reduction of area φ is obtained, as shown in Fig. 15.

3.4 Initiation of local shrinkage under cyclic load

As seen from Fig. 13(b), an increase in maximum plastic strains ϵ_{pmax} is remarkable with specimens which suffer local shrinkage during tests, that is, in the cases of necked-out fracture-type and intermediate fracture-type, and the increase is not so remarkable with specimens which do not suffer local shrinkage, that is, in the case of fatigue fracture-type. So, the

Fig. 16 Relation between value of m and maximum plastic strain ϵ_{pmax}
(F: Fatigue fracture-type, I: Intermediate fracture-type, N: Necked-out fracture-type,
 ϵ_{ps} : Plastic strain at the beginning of local shrinkage in static tensile test)

Fig. 17 Relation between value of m and plastic strain ϵ_p in static tensile test

relations between maximum plastic strain $\epsilon_{p\max}$ during load-cycling and values of m representing the shape of specimens are investigated, and the results are shown in Fig. 16. Dotted lines in this figure show that maximum plastic strain $\epsilon_{p\max}$ is equal to the plastic strain ϵ_{ps} at the beginning of the increase in value of m in static tensile test (the relation between plastic strain and value of m is shown in Fig. 17). It is found from Fig. 16 that maximum plastic strains are smaller than the plastic strain indicated with dotted lines for the specimens which do not suffer local shrinkage (in the cases of fatigue fracture-type) but they become larger than the plastic strain indicated with dotted lines after certain load-cycles with specimen which suffer local shrinkage (in the cases of necked-out fracture-type and intermediate fracture-type), and that the increase in value of m under cyclic load begins approximately at the plastic strain indicated with dotted lines. Accordingly, from the above-mentioned fact, it is found that the initiation of local shrinkage under cyclic load occurs when the maximum plastic strain caused by cyclic load equals the plastic strain at which local shrinkage

begins to occur under static tensile load.

4. Conclusions

It has been known under load-controlled low-cycle fatigue test that there are two different types of fractures—fatigue fracture-type and necked-out fracture-type. In addition to these two types of fractures, it is empirically known that there is an intermediate type between the two types above-mentioned, that is to say the fatigue type fracture following some local shrinkage.

These points will give some useful scientific basis to judge the reasons of the fractured structures.

In this report, the mechanism of these three types of fracture also is discussed from different points of view.

Acknowledgement

In preparing this presentation, the authors wish to extend their gratitude to Mr. S. Tanaka for his assistance, and also to Komai Tekko Co. and Sakai Tekko Co. for their support.

References

- (1) Watanabe, M., et al., *J. Weld. Soc.* (in Japanese), Vol. 40, No. 7 (1971), p. 640.
- (2) Benham, P.P., *Jour. Inst. Metal*, Vol. 89 (1960-61), p. 328.
- (3) Benham, P.P., et al., *Jour. Mech. Eng. Sci.*, Vol. 3 (1961), p. 119.
- (4) Shiratori, E., et al., *Trans. Japan Soc. Mech. Engrs.* (in Japanese), Vol. 35, No. 272 (1969-4), p. 711.
- (5) Uemura, M., *Trans. Japan Soc. Mech. Engrs.* (in Japanese), Vol. 23, No. 127 (1957-3), p. 148.
- (6) Terazawa, K., et al., *J. Soc. Naval Arch.* (in Japanese), Vol. 123 (1968), p. 274.
- (7) Raymond, M.H., et al., *Jour. Basic Eng., Trans. ASME, Ser. D*, Vol. 85 (1963), p. 548.

Discussion

E. SHIRATORI (Tokyo Institute of Technology):

In Fig. 9 and Fig. 14, an intermediate fracture-type exists as the transitional fracture-type between 100% fatigue fracture-type and 100% necked-out fracture-type. So, if any correlation between the mixed rate of both fracture-types and φ or r is found, we can make clear the limited values of φ and r in each fracture-type. Did you have any try at this point?

Authors' closure

Three fracture-types indicated in this report are distinguished for convenience according to the condition of occurrence of fatigue crack and local shrinkage, i.e., the limit between fatigue and intermediate

fracture-type is defined according to the condition which phenomenon, local shrinkage or fatigue crack, occurs for the first time and the necked-out fracture-type is defined for the case when there is not any fatigue crack, as shown in Append.-Fig. 1.

If we denote the percentage of fatigue fracture-surface-area for whole fracture-surface-area with $\sum F/A$ (A : whole fracture-surface-area, $\sum F$: total fatigue fracture-surface-area), the correlation between $\sum F/A$ and the reduction of area $\varphi\%$ measured after failure is plotted in Append.-Fig. 2. As you see from Append.-Fig. 2, $\sum F/A$ becomes smaller and smaller as φ becomes larger and larger. However, it goes without saying that φ value is affected not only by the types of fracture-surface but also by the deformation

Append.-Fig. 1 Appearances of fracture-surface for three fracture-types

near the fractured position.

From such a point of view, we did not discuss the meaning of the limit values of φ (or r). About this point, we intend to investigate in future using more data in accordance with your advice.

Append.-Fig. 2 Relation between reduction of area and percentage of fatigue fracture-surface