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MONOTONOUS STRESS-STRAIN PROPERTIES OF STRUCTURAL STEEL SUBJECTED TO NONSTATIONARY REPETITIVE PRE-LOADING

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Key Words ;Hysteretic Effects, Inelastic Range, SM58Q, SM41.

1. INTRODUCTION

Structures are reliably subjected to severe repetitive loads due to earthquakes, wind storms, waves and so on in Japan. Such structures have to be designed under considerations for the responses to those fluctuating forces, and mechanical properties of material used are one of the important factors to rate the responses. Generally speaking, the effects of loading history with inelastic strainings have to be discussed in view of the following two points: (1)low cycle fatigue, (2)accumulation of deformation due to cyclic inelastic strain[1] . The progress of failure in steel structures has been investigated in accordance with those two points up to the present. However, structural properties may be changed by the "hysteretic effect" due to accidental loads and after being subjected to such accidental loads the behaviors of the structure under ordinary loads may not always be kept up in the same as that predicted in design.

Many researches on properties of structural steel subjected to inelastic monotonous loads or stationary repetitive loads have been performed with the purpose of ensuring the structural safety under such loading histories [2]~[6]. According to the results, it is clear that mechanical properties of structural steel are affected by inelastic loading histories. However, mechanical properties of structural steel previously subjected to nonstationary repetition of stress or strain are not known in detail due to the lack of experimental data. In this study, in order to investigate the mechanical properties of structural steel which had previously been subjected to nonstationary repetitive uniaxial loads, monotonous tension or compression loading tests of steel specimens were carried out.

2. LOADING TESTS

(1)Specimens and Testing Apparatus

Structural steels of SM41A and SM58Q were tested. Table.1 shows the mechanical properties and chemical compositions of the steels presented by the steel maker. In this table, the data for SM58Q-2 were obtained by authors' tension tests. The configuration of test specimens used is illustrated in Fig.1. Round-bar specimens of 18mm in diameter were finished from a steel plate of 32mm in thickness.

In cyclic plasticity tests, hourglass specimens are generally used. By using such specimens, however, accurate stress-strain relations are not always obtained because of

Table.1 Mechanical Properties and Chemical Compositions.

Material	Tension test			Chemical composition %					
	Y.P. N/mm2	T.S. N/mm2	EL. %	C x100	Si x100	Mn x100	P x1000	S x1000	Ceq. x100
SM58Q-1	588	696	28	14	29	129	21	3	42
SM58Q-2	529	617	42	-	-	-	-	-	-
SM41A	353	470	31	19	22	80	14	14	33

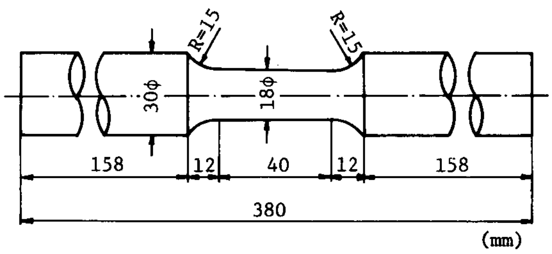

Fig.1 Configuration of Specimens.

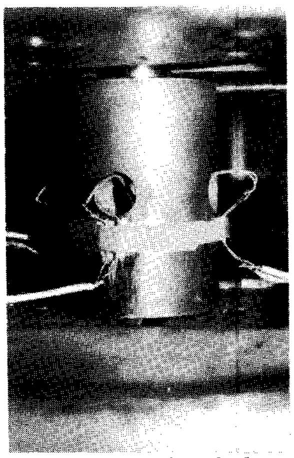

Photo.1 Steel Tubular Stiffener.

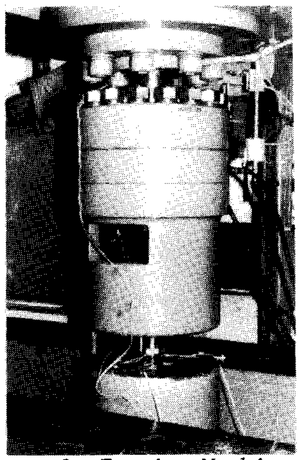

Photo.2 Testing Machine.

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the presence of stress gradient in a direction of specimen axis(7),(8). Therefore, the specimens with constant section in a test region were used in this tests. It is important, in this case, to prevent specimens from buckling or bending during compressive loading processes. In this experimental study, a steel tubular stiffener of 22mm in thickness was installed around a specimen to eliminate the such undesirable phenomena as shown in Photo.1, and dry-bearing-metals were filled in the gap between the stiffener and a specimen to decrease frictions.

A testing machine with 50ton capacity tension-compression pulsator was employed. Photo.2 shows the oil pressure chucking system used for setting the specimens. A magnetic tape recorder was used to memorize the load detected by a load-cell attached to the testing machine and the strain by inelastic range strain gages. In addition, relations between the load and the strain were drawn on a X-Y recorder at tests. Axial elongation, which was converted into axial strain by using the elongation-strain calibration curve prepared, was also measured by a differential transformer installed between two grips of a specimen.

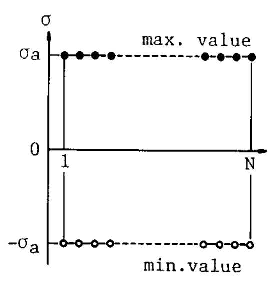
(2)Loading Rules

The tests were performed under following pre-loading histories prior to the uniaxial tension or compression loading tests:

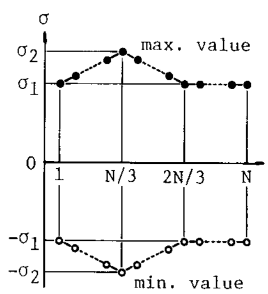
- Series (I) ; reversed cyclic loading with constant nominal stress amplitude,
- Series(II) ; reversed cyclic loading whose nominal stress amplitude was at first gradually increased, then decreased and finally kept constant,
- Series(III); pulsating cyclic loading whose strain amplitude was gradually decreased.

Figure.2-(1) shows a scheme of loading history for series (I), where σ_a indicates stress amplitude chosen as either 95% or 110% of the yield strength for SM58Q, and either 80% or 90% of the tensile strength for SM41A. The scheme for series (II) is shown in Fig.2-(2). Minimum stress amplitude denoted by σ_1 is fixed to the yield strength, while maximum stress amplitude denoted by σ_2 corresponds to 110% of the yield strength for SM58Q and 90% of the tensile strength for SM41A. For specimens subjected to the loading history indicated by series (I) and (II), tension tests were performed after keeping the materials at 100°C for 60 minutes in order to investigate the effects of the strain aging. Materials tested were SM41A and SM58Q-1.

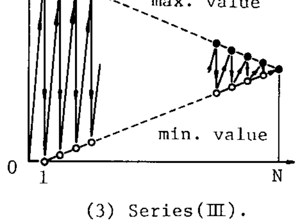
In series (III), loading and unloading were repeated along the strain path as shown in



(1) Series(I).

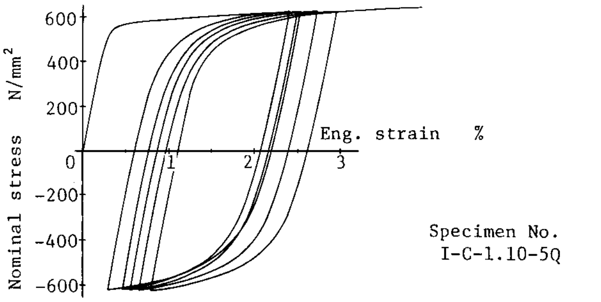


(2) Series(II).

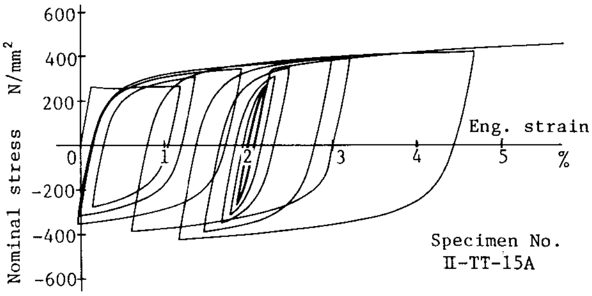


(3) Series(III).

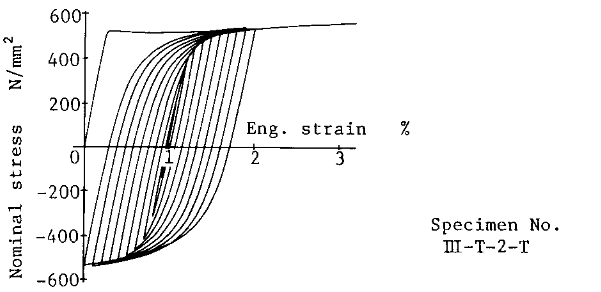
Fig.2 Loading History Schemata.



(1) Series(I).



(2) Series(II).



(3) Series(III).

Fig.3 Examples of Test Results obtained from Pre-loadings.

Fig.2-(3) which followed by the strain amplitude converging to zero. Tension tests were carried out before the effect of strain aging appeared. In this series, compression tests were additionally performed to compare with the results by tension tests.

(3)Classification of Testing Conditions and Their Notations

Each series of loading histories was classified in detail as follows:

Series(I) ;I - ⓑ - ⓒ - ⓓⓖ (e.g.:I-T-0.9-10A),
Series(II) ;II - ⓐⓑ - ⓓⓖ (e.g.:II -TC-15Q),
Series(III);III- ⓐ - ⓔ - ⓕ (e.g.:III-T-4-C),

where ⓐ denotes sign of initial yielding ("T" in tension, "C" in compression),
ⓑ denotes sign in the last loading path in pre-loading ("T" in tension, "C" in compression),
ⓒ indicates the ratio of stress amplitude to the yield strength for SM58Q and to the tensile strength for SM41A respectively,
ⓓ indicates total number of cycles (cycle),
ⓔ indicates maximum strain amplitude $= \varepsilon_1(\%)$,
ⓕ denotes loading direction of the test after cyclic pre-loading ("T" in tension, "C" in compression),
ⓖ indicates material ("Q" for SM58Q "A" for SM41A).

Examples of test results obtained from repetitive pre-loading tests in each series are shown in Fig.3-(1)∿Fig.3-(3). The strain shown in the above figures is detected by strain gages.

3. STRESS-STRAIN RELATIONS

(1)Experimental Results

Stress-strain curves obtained by tension tests of specimens previously subjected to the loading of series (I) are contained in the shadowed domain in Fig.4. Figures.5 and 6 show the stress-strain relations of materials previously subjected to the loadings of series (II) and (III), respectively. In these figures, the ordinate shows the true stress based on the assumption that volume is constant under inelastic deformation, and the plastic logarismic strain, which is calculated from the strain detected by strain gages, is taken as the abscissa. It should be noted that strain in these figures is restricted in the range of $0 \leqq \varepsilon_p \leqq 5\%$.

(2)Discussions

When mild steel is inelastically stretched, unloaded and then kept under no load for a long while, generally yield plateau recovers and the yield strength increases by strain aging. To the contrary, when the specimen is loaded again in the opposite direction immediately after unloading, yield plateau is not observed, and decrease of yield strength becomes notably by Bauschinger effect, and this effect vanishes out by strain aging[2] . Though the experimental results obtained from the monotonous loading tests on steel specimens in series (I) and (II) do not perfectly correspond to the above stated phenomena, it is expected that certain corresponding phenomena will be observed because the loading tests in series (I) and (II) were finished through unloading path from certain levels of tensile or compressive stress.

The experimental results of series (I) and (II) are classified into two groups: in one group yield plateau recovered and in the other not. Yield plateau could be seen only in the case of T-type specimens in series (I). Study by Nishimura and Miki[6] on tensile stress-strain properties of materials previously subjected to repetitive loading of constant strain amplitude reported the tendency in which yield plateau was not observed. Thus, it can be probably concluded that when steel is subjected to repetitive loadings in inelastic range, yield plateau vanishes.

Stress-strain relations of series (I) and (II) are also classified into following two groups: one group has a property that stress corresponding to some amount of plastic strain was greater than that in virgin material, and the other has a opposite tendency. In this paper, the former property is denoted as "state of hardening" and the latter as "state of softening".

Preloaded SM41A are always in the state of hardening and the rate of hardening is notable in T-type specimens in series (I). Bauschinger effect is observed in the range of smaller strain for C-type specimens of series (I) and TC and CC-type specimens of series (II) , where last loading paths in pre-loading tests were in compression. And the rate of hardening in these cases is slightly less than that in the cases where last loading paths in pre-loading were in tension, but the rate in series (II) does not depend on the loading direction of last path in the range of larger strain.

Randon et al.[9] reported that steel in a state of hardening under repetitive loads of constant stress amplitude tended to be in the stationary state independent of the loading histories. Differences between the patterns of stress-strain curves of preloaded SM41A in series (II) are not affected by whether the initial yielding is in tension or not. The above mentioned results are explained by the fact that the relation between number of cycles and plastic strain amplitude became stationary as shown in Fig.7. These experimental results suggest that an inelastic repetitive straining does not always impaire stress-strain properties of mild steel such as SM41A.

Preloaded SM58Q tends to be in the state of hardening like the state for preloaded SM41A when the last loading path in pre-loading is in tension. When the last loading path is in compression the SM58Q tends to be in the state of softening and Bauschinger effect can be remarkably observed in the range of smaller

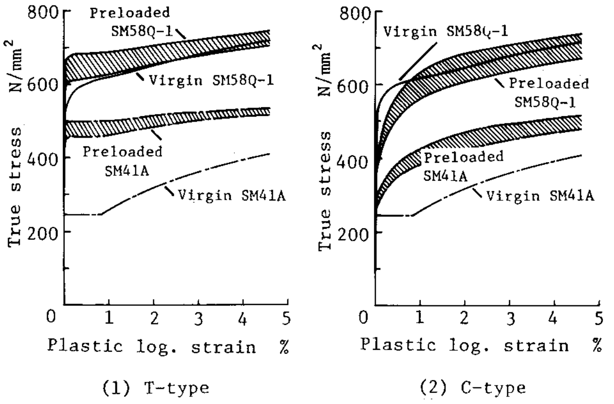


Fig.4 Stress-Plastic Strain Diagrams (series(I)).

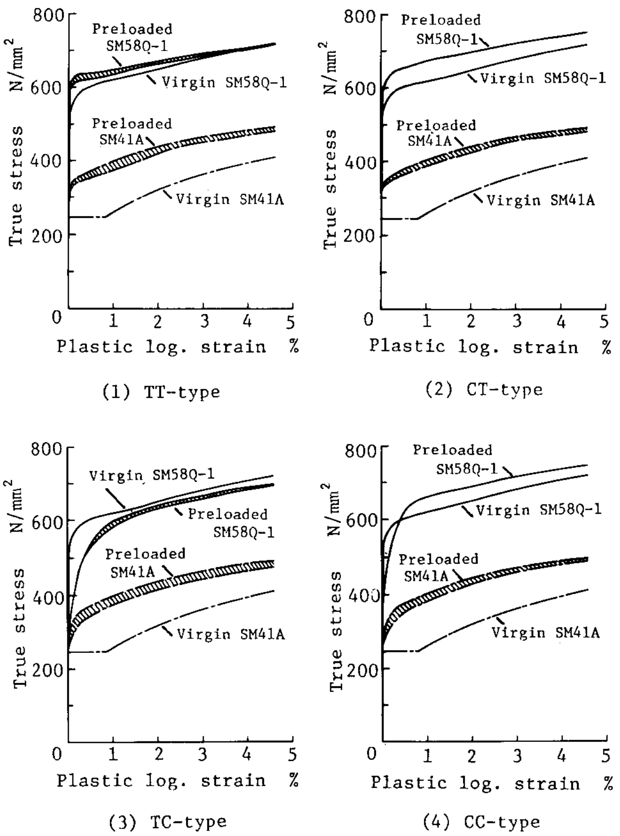
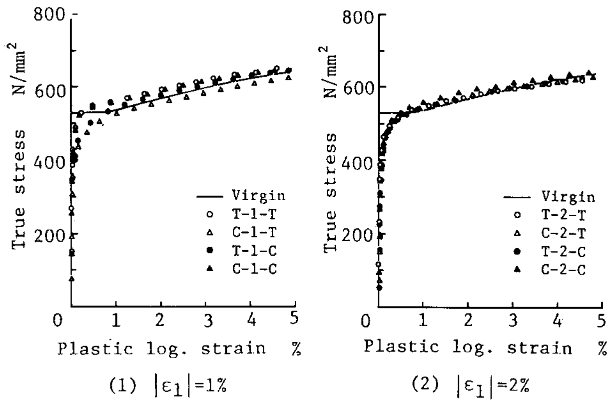


Fig.5 Stress-Plastic Strain Diagrams (series(II)).



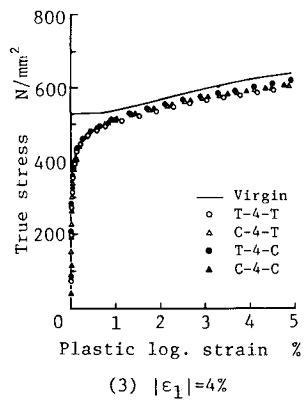


Fig.6 Stress-Plastic Strain Diagrams (series(III)).

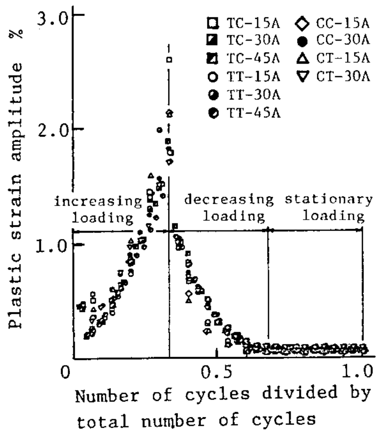
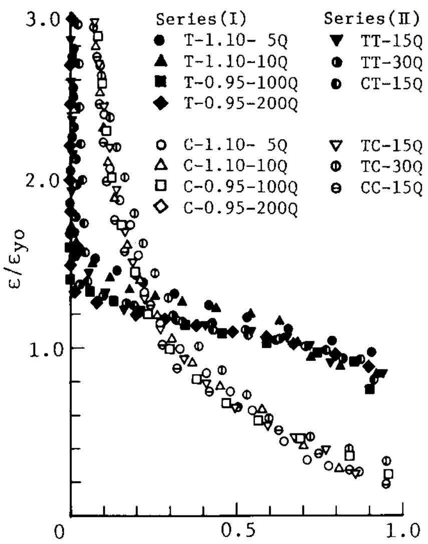


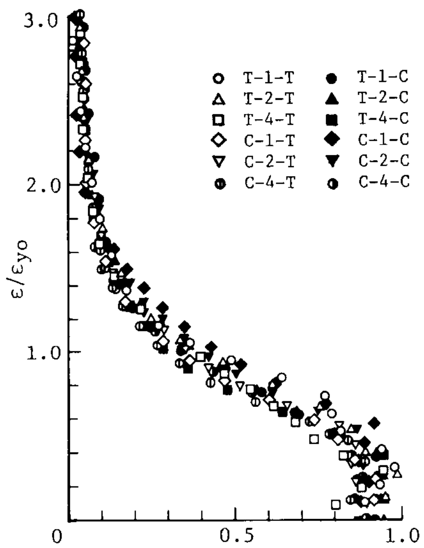
Fig.7 Plastic Strain Amplitude on Number of Cycles of SM41A in series(II).

strain.

To remove the effect of the last loading path in pre-loading as mentioned above, the test specimens made by SM58Q-2 in series (III) were subjected to the loading histories where strain amplitude was gradually decreased and then converged to zero. Stress-strain relations depended on the absolute value ($|\varepsilon_1|$) of maximum strain amplitude are gained. When $|\varepsilon_1|$=2%, stress-strain relations of preloaded materials are preferably in good agreement with that of virgin material except for the neighbourhood of yield plateau. In the case where $|\varepsilon_1|$=4%, preloaded materials are in the state of softening over all the strain range. In these two cases, any difference due to whether the initial yielding occures in tension or in compression and whether the test



(1) Series(I) & (II)



(2) Series(III)

Fig.8 Nondimensional Tangent Modulus-Nondimensional Strain Diagrams of Preloaded SM58Q.

performed is a tension test or a compression test, is scarcely seen in the stress-strain relations. T-T and C-C specimens with $|\varepsilon_1|$ =1% are in the state of hardening, while T-C and C-T specimens are in the state of softening and the rate of softening are almost identical with that of $|\varepsilon_1|$=2%.

4. TANGENT MODULUS-STRAIN RELATIONS

(1)Experimental Results

In the field of structural mechanics, tangent modulus plays an important role as a value by which a lower limit of ultimate load capacity of columns or beam-columns is provided, and it is an important characteristic value to study unstable phenomena in inelastic range[10] . It is also a characteristic value from the viewpoint of fracture mechanics. The stress causing the unstable growth of micro crack is connected with the yield strength by the tangent modulus[11] .

Figure.8-(1) shows the relations between the tangent modulus (E_T=$d\sigma/d\varepsilon$) normalized by Young's modulus (E) on the abscissa and the strain (ε) normalized by yield strain (ε_{yo}=σ_{yo}/E) on the ordinate for preloaded SM58Q-1 of series (I) and (II). Figure.8-(2) shows the corresponding relations for preloaded SM58Q-2 of series (III). The results shown in Fig.8 are in true stress evaluated from the assumption noticed before and in plastic logarismic strain. In these figures strain is restricted to the range of $0 \leqq \varepsilon/\varepsilon_{yo} \leqq 3$

(2)Discussions

As shown in Fig.8-(1), obvious difference can be observed in $\varepsilon/\varepsilon_{yo}$-$E_T/E$ relations for series (I) and (II). And the difference is due to the last loading path in pre-loading, which is in tension (T-type in series (I), TT and CT-type in series (II)) or in compression (C-type in series(I), TC and CC-type in series (II)).

In the former case, the tangent modulus decreases rapidly and linearly according as the strain increases over the yield strain, and the values of that are small and nearly constant at the strain over the range of $\varepsilon/\varepsilon_{yo}$=1.4∿1.6. When the stress amplitude is 110% of the yield strength for T-type specimens in series (I) (the data are illustrated by the marks ● and ▲ in Fig.8-(1) and in the case where yield plateau is observed as shown in Fig.4-(1)), the strain corresponding to the same value of the tangent modulus is remarkably greater compared with other specimens. This result is mainly caused by strain hardening.

In the latter case, owing to Bauschinger effect the tangent modulus decreases gradually as the strain increases from a strain in the range of $\varepsilon/\varepsilon_{yo}$=0.2∿0.4, and $\varepsilon/\varepsilon_{yo}$-$E_T/E$ curve is concave up. At $\varepsilon/\varepsilon_{yo}$=0.5, E_T/E is equal to 0.6∿0.7, and at $\varepsilon/\varepsilon_{yo}$ =1.0, E_T/E is equal to 0.3∿0.4. The $\varepsilon/\varepsilon_{yo}$-$E_T/E$ curves of the both cases, moreover, intersect each other at the point of $\varepsilon/\varepsilon_{yo}$=1.2 (or E_T/E=0.3), so that in the range where strain is more than $\varepsilon/\varepsilon_{yo}$=1.2 the tangent modulus for the latter case is greater than that for the former case on the same strain.

In the case of series (III), the tangent modulus tends to decrease when $\varepsilon/\varepsilon_{yo}$=0.4∿0.6. And over a strain range of $\varepsilon/\varepsilon_{yo} \leqq 1.2$, it is greater than that for those specimens in series (I) and (II) whose last loading paths in pre-loading were in compression, while in the case of $1.2 \leqq \varepsilon/\varepsilon_{yo}$ the relation is reversed.

From the above discussions, the following summaries are obtained:

(1)The results of series (I) and (II) reveals that $\varepsilon/\varepsilon_{yo}$-$E_T/E$ relations vary with the direction of the last loading path in pre-loading.

(2)When the last loading paths in pre-loading are in tension, the change of tangent modulus is smaller than that of virgin material.

(3)In the case where the last loading paths in pre-loading are in compression, the tangent modulus tends to decrease at the small strain, for example $\varepsilon/\varepsilon_{yo}=0.2\sim0.4$. This result seems to imply the remarkable decrease of the stiffeness of materials.

(4)In series (III), obvious difference in $\varepsilon/\varepsilon_{yo}$ -E_T/E relations due to the test conditions is not observed. The decrease of tangent modulus as compared with that of virgin material is hard, but the rate of decrease is not so remarkable comparing with the results of those experiments for series (I) and (II) whose last loading paths in pre-loading are in compression.

It is clear that the tangent modulus for SM58Q decrease remarkably in all cases when subjected to repetitive loads, and this reveals that the study on ultimate load capacity of structural members made by such materials has to be pursued.

5. TENSILE STRENGTH

(1)Experimental Results

Table.2 indicates the ratio of the tensile

Table.2 Changes in Mechanical Properties by Pre-loadings.

(1).Series(I)

Specimen No.	$\tilde{\sigma}_B/\sigma_B$	$\tilde{\sigma}_y/\sigma_{yo}$
C-0.8-25A	1.00	1.17
C-0.8-50A	0.98	1.16
C-0.8-75A	0.98	1.19
C-0.9- 5A	1.02	1.25
C-0.9-10A	0.98	1.23
T-0.8-25A	1.01	1.63
T-0.8-50A	0.99	1.63
T-0.8-75A	1.00	1.62
T-0.9- 5A	1.01	1.77
T-0.9-10A	1.00	1.77
C-1.1- 5Q	0.98	0.79
C-1.1-10Q	0.99	0.78
C-0.95-100Q	0.98	0.77
C-0.95-200Q	0.95	0.73
T-1.1- 5Q	0.98	1.14
T-1.1-10Q	1.00	1.11
T-0.95-100Q	0.97	1.02
T-0.95-200Q	0.99	1.04

(2).Series(II)

Specimen No.	$\tilde{\sigma}_B/\sigma_B$	$\tilde{\sigma}_y/\sigma_{yo}$
TC-15A	1.01	1.31
TC-30A	1.01	1.22
TC-45A	1.00	1.19
TT-15A	1.03	1.35
TT-30A	1.03	1.28
TT-45A	1.01	1.28
CC-15A	1.03	1.34
CC-30A	1.02	1.19
CT-15A	1.01	1.36
CT-30A	1.01	1.32
TC-15Q	0.98	0.76
TC-30Q	0.97	0.77
TT-15Q	0.97	1.05
TT-30Q	0.98	1.08
CC-15Q	1.04	0.87
CT-15Q	1.04	1.07

(3).Series(III)

Specimen NO.	$\tilde{\sigma}_B/\sigma_B$	$\tilde{\sigma}_y/\sigma_{yo}$
T-1-T	1.01	0.99
T-2-T	0.96	0.96
T-4-T	0.93	0.86
C-1-T	0.99	0.84
C-2-T	0.99	0.90
C-4-T	0.98	0.82
T-1-C	-	0.88
T-2-C	-	0.90
T-4-C	-	0.88
C-1-C	-	0.98
C-2-C	-	0.93
C-4-C	-	0.83

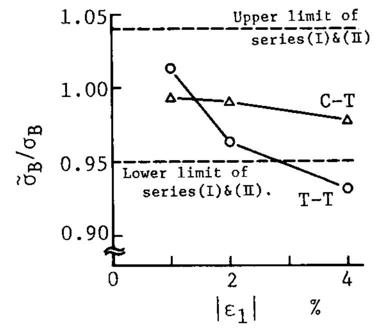


Fig.9 Relations between $\tilde{\sigma}_B/\sigma_B$ and $|\varepsilon_1|$ in series(III).

strength ($\tilde{\sigma}_B$) of preloaded materials to the tensile strength (σ_B) of virgin material and that of the yield strength ($\tilde{\sigma}_y$) of preloaded materials to the initial yield strength (σ_{yo}) of the same materials. The yield strength implies lower yield strength or the stress corresponding to 0.2% offset strain.

(2)Discussions

In series (I), the tensile strength changes by ±2% for SM41A and -1%∿-5% for SM58Q. In the case of SM41A under pre-loading with a specified stress amplitude, the tensile strength tends to decrease as number of cycles increases. However, the effect of stress apmlitude and the direction of the last loading path in pre-loading on the tensile strength is not evident and the tendency of the change in the tensile strength for SM58Q is not clear.

Kato et al.[1] suggested that (1)slow increase of tensile strength for SM41A and slow decrease for SM58Q was accompanied by the increase in number of cycles, (2)the tensile strength increased by 0∿10% for SM41A and decreased by 0∿10% for SM58Q, and (3)those changes did not depend on stress amplitude, according to the similar experiments to the authors'. However, so far as the authors' results are concerned, the variance of tensile strength is very small.

In series (II), the increase of tensile strength for SM41A is 0∿3%. Whether the initial yielding and the last loading path in pre-loading is in tension or not does not contribute to increase in the tensile strength. The decrease of tensile strength for SM58Q is 2%∿3% when initial yielding is in tension, and increase of that is about 4% when initial yielding occures in compression.

Figure.9 shows the relation between $\tilde{\sigma}_B/\sigma_B$ and the absolute value of maximum strain amplitude ($|\varepsilon_1|$) of the loading histories in series (III). In the figure, the lower limit and upper limit of $\tilde{\sigma}_B/\sigma_B$ of series (I) and (II) is shown. Being accompanied by increase of $|\varepsilon_1|$, the tensile strength is decreasing from +1% to -7% for the initial yielding in tension and decreases by 1%∿2% for the initial yielding in compression. The rate of change in tensile strength is much the same as that of series (I) and (II) except III-T-4-T' specimen. The tensile strength of specimens with initial yielding in tension tends clearly to decrease according as $|\varepsilon_1|$ increases.

As mentioned above, the tensile strength seems to depend on $|\varepsilon_1|$ or residual plastic strain, when specimens have been subjected to the gradually decreasing strain amplitude such as series (III). Up to this time, no study is carried out on the tensile strength of materials subjected to the nonstationary repetitive loads such as series (II) and (III), and therefore there is no experimental result to be comarable with the results obtained here. Excessive loads to which structures are supposed to be subjected, are generally nonstationary. According to the authors' study, the tensile strength changes by a few percent of virgin material, and in the case of the initial yielding in tension of series (III) , the more severe the loading, the less the tensile strength.

6. CONCLUDING REMARKS

From experimental results and discussions in this paper, it is clear that (1)repetitive loading in inelastic range does not always bring disadvantageous effect on hardening materials such as SM41A, but (2)the loading brings worse material changes for softening materials such as SM58Q and the more severe the loading given, the more remarkable this tendency. Investigations have to be widely carried out on behaviors of structures or structural members made by softening materials.

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