INELASTIC BEHAVIOR OF HIGH STRENGTH STEELS UNDER CYCLIC GRADIENT STRESS

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ABSTRACT

High-strength steels have by current Japanese building law not been permitted to be used in seismic designed structures owing to the high yield ratio (yield strength over ultimate tensile strength) and lack of inelastic deformation capacity. In recent years, a new rational seismic design method called "Damage Tolerant Structure" has been proposed. This method assumes that the building structure is composed of two independent parts – the primary structure and the brace system. The primary structure is manufactured using high-strength steels that have large elastic deformation capacity. The brace system is made of extra-low-strength steels that can yield at low stress and have large inelastic deformation capacity to dissipate the earthquake energy efficiently. It is considered that suitable combination of high-strength steels with extra-low-strength steels will certainly construct some more rational seismic design approaches. It is necessary to investigate the inelastic mechanical properties of high-strength steels in case of an earthquake so large earthquake that even the high-strength steel yields. This paper reports some results of cyclic loading experiment using high-strength steels whose strengths ranged from 800MPa to 600MPa. For the purpose of comparison, the cyclic loading experiment for plain strength steel SS400 is also carried out.

KEYWORDS

High-strength steels, Seismic design, Steel structure, Cyclic loading experiment, Gradient stress

INTRODUCTION

In the long history of mankind, humans managed to build shelters to protect themselves against natural disasters, such as heavy rain and flood, tornadoes and strong wind, as well as large earthquakes, etc. Buildings as one kind of shelters are developed and improved constantly by mankind during their struggles with the natural disasters. It is well known that building materials have made great progress from soil, stone, brick, straw and wood in the ancient times into concrete, steels and many new chemical materials at present. However, humans cannot escape the threat of earthquakes even today when the science and technology is so highly developed. For example, in January 17, 1995, an extreme large earthquake hit the south area of Hyougo-prefecture of Japan, and over 5400 people died, over thirty thousand peoples were injured and damage of more than ten trillion Japanese Yen of economic loss is estimated to have occurred. On January 17, 1994, a large earthquake hit the Northridge area of USA. There was a great loss of human life and economic disruption since many civil engineering projects and building structures were damaged or collapsed (Krawinkler, 1994).

In the traditional approaches of structural seismic design, a building structure passively resists earthquake ground motion through a combination of strength, deformability and energy dissipation. Much of an

earthquake's energy is dissipated by the localized damage of primary structure (i.e. beams, columns and connecting panels) which has the primary role of supporting vertical load. Experience with recent earthquakes happening in Japan and USA has shown that even though properly designed structures survived, the cost of repairing the damage was considerably more than had been anticipated since the primary structure was damaged severely due to the large inelastic deformation (Connor, 1992). To use high-strength steels that have large elastic deformation capacity can protect the primary structure against large inelastic damage (Wada et al., 1992). High-strength steels, however, have not been allowed to be used in the seismic designed structures by the current Japanese building laws owing to the high yield ratio (yield strength over ultimate tensile strength) and lack of inelastic deformation capacity. It is necessary to investigate the inelastic mechanical properties of high-strength steels under cyclic loading in case of an extreme seismic excitation, even though the high-strength steels are assumed to be used in the elastic range.

Much research can be found in the field of studying high-strength steels (Yamashita et al., 1993; Iwata and Wada et al., 1992, 1993). The critical problem of steel structure during earthquake excitation is lack of ductility in the beam-ends. One of important characteristics of actual steel beams is of gradient stress or stress concentration near the beam-ends. It has been pointed out that the inelastic deformation capacity or ductility of steel members with gradient stress is strongly dependent on the mechanical properties, especially the yield ratio (Aoki and Kato et al., 1982).

In this experimental study, we used two kinds of 600MPa class (WT590) and 800MPa class (WT780) high-strength steels and considered the influence of different yield ratios. In order to simulate the real states of stress distributed in the actual beam-ends, we used specimens with four kinds of different tapered section that can produce gradient stress. A buckling-resistant system was developed to prevent the specimens from buckling under the compression load. The cyclic loading experiment was carried out under a quite stiff test machine controlled by a personal computer according to the measured displacement.

OUTLINES OF EXPERIMENT

The approximate moment distribution in a actual structural beam under the action of vertical and lateral loadings is illustrated in Fig. 1(a). The stress distribution at the outside edge of the actual beams is approximately illustrated in Fig. 1(b). The stress near the span center is smaller than those near the

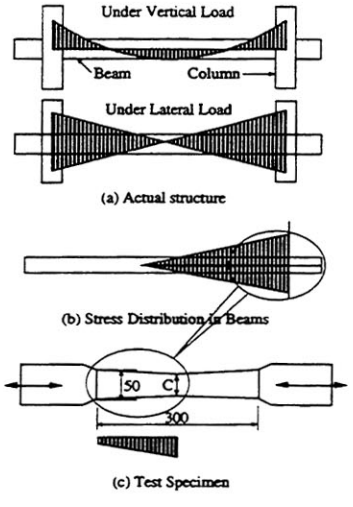
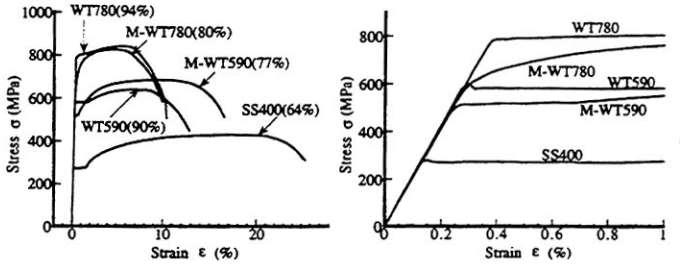


Fig. 1 Outline of specimen



(a) Global relationship (b) Local extension within 1%

Fig. 2 Relations of stress and strain of the steels

Table 1 Mechanical properties under monotonous tension

STEEL	Young's ratio(10^5)	σ_y (MPa)	σ_{max} (MPa)	Elongation ratio at maximum strength (%)	Elongation ratio(%)
WT780	21.2	802	860	6	10
M-WT780	21.3	702	844	5	10
WT590	21.7	593	654	7	13
M-WT590	21.2	523	699	11	17
SS400	21.4	281	440	18	25

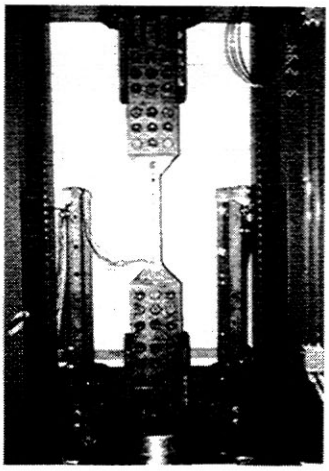


Photo 1. Installation

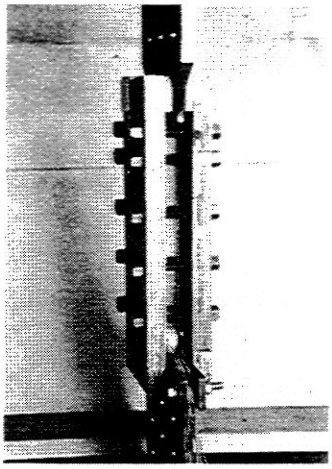


Photo 2. Buckling-resistant system

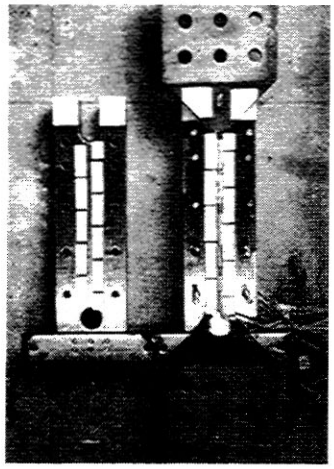


Photo 3. Stiff plates

beam-ends since the moment near span center is smaller than that of beam-ends if the lateral loading is dominant compared to the vertical loading. If the frame structure is used as the specimen, it will be very difficult to carry out a great number of experiments to simulate various of different situations. Therefore, a family of scaled small test specimens with tapered section shown in Fig. 1(c) were prepared for the cyclic loading experiments. The stress distribution produced in the specimens whose gradient is proportional to the sectional variation simulates the real stress distribution of actual beams shown in Fig. 1(b). The length of specimens producing inelastic deformation is 300mm and the thickness is 19mm. The end width of test part of the specimen is 50mm. Four kinds of center width of specimen (50mm, 48mm, 45mm and 40mm) are considered to generate 4 kinds of different gradient stress distribution in the specimen.

The steel categories used in the cyclic loading experiment are illustrated in Fig. 2. The values in parenthesis after the steel name denote yield ratio of the steel. WT780 stands for 800MPa class high-strength steel and WT590 stands for 600MPa class high-strength steel. The head character 'M' in the name of M-WT780 and M-WT590 means modified high-strength steel whose yield ratio is smaller than that of plain high-strength steels (WT780 and WT590). For the purpose of comparison, cyclic loading experiment for the plain strength steel SS400 is also carried out. It is obviously known in Fig. 2(b) that the elastic deformation range of high-strength steels is 2~3 times larger than that of SS400. The mechanical properties of the applied steels under monotonous tensile loading are shown in Table 1.

Cyclic loading experiments with equal amplitude compression and tension were carried out under a large test machine AG-150TD that is so stiff that it can be controlled by displacement. Photo 1 shows the installation of specimen in the test machine. In order to prevent the specimen from buckling under a large compression load, a buckling-resistant system shown in Photo 2 was developed. Test specimen was sandwiched by two stiff

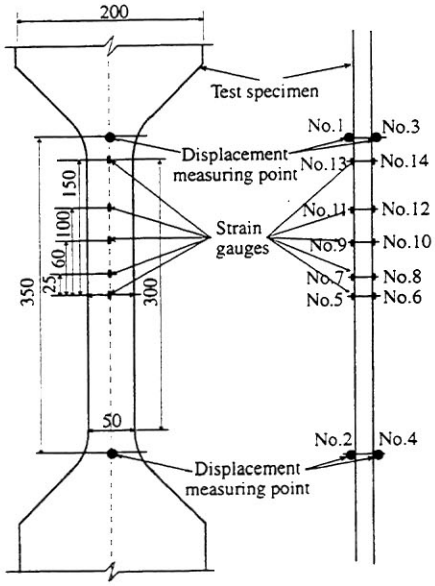


Fig. 3 Measuring points of strains and displacements

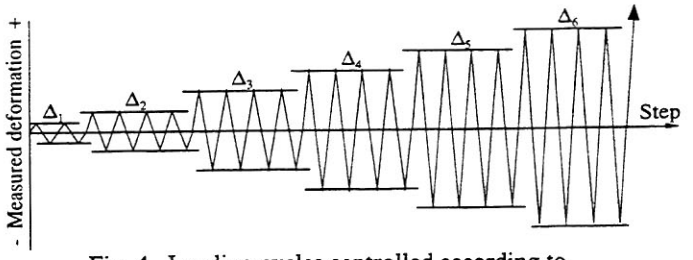


Fig. 4 Loading cycles controlled according to the measured deformation

Table 2 Controlled level of deformation

	WT780, M-WT780	WT590, M-WT590	SS400
Δ_1	0.1%L	0.1%L	0.1%L
Δ_2	0.3%L	0.2%L	0.2%L
Δ_3	0.4%L	0.4%L	0.4%L
Δ_4	0.6%L	0.6%L	0.6%L
Δ_5	0.8%L	0.8%L	0.8%L
Δ_6	1.0%L	1.0%L	1.0%L

plates (130mm×30mm×480mm) using 10 bolts. Some small steel plates (20mm×9mm×55mm) were arranged between the specimen and the stiff plates shown in Photo 3. A groove was provided in the center between small steel plates for the lead lines of strain gauges. In order to have the test specimen slide against the stiff plates freely, two pieces of 1mm thick Teflon sheets were inserted between the specimen and small steel plates; the surfaces of the Teflon sheets were spread with silicon lubrication oil.

Measuring points of strains and displacements are shown in Fig. 3. Strains are measured in 5 sections at two sides (No.5~14) along with the axial longitudinal direction of the test specimen and the average values of two sides are taken. The elongation deformation of test specimen can be obtained from the displacements that are measured from 4 positions at two ends of test specimen (No.1~4).

The loading cycles controlled by the measured deformation is shown in Fig. 4. The controlled levels for the deformation shown in Table 2 are different in correspondence with different steels.

HYSTERESIS OF STRESS AND STRAIN

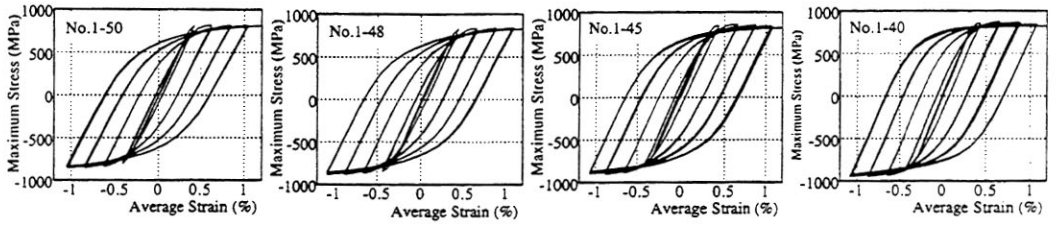
The cyclic loading experiments with equal amplitude compression and tension were carried out until 1.0%L elongation deformation. The obtained hysteresis of stress and average strain are illustrated in Figs. 5(a)~(e). The maximum stress in Figs. 5(a)~(e) is evaluated from the loads divided by the minimum sectional area and the average strains are obtained from the measured axial elongation divided by the target distance between the measuring points at two ends.

It is found that the inelastic strength of both WT590 class and WT780 class high-strength steels decreases with the loading cycle number increases.

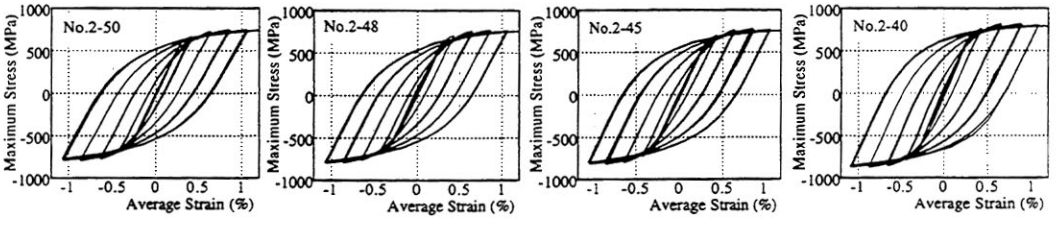
When the gradient stress increases, the curve part of the hysteresis loop of stress and average strain expands greater for high-strength steels than that for SS400 steel. It could be said that the strain energy of one single cycle for high-strength steels increases with the gradient stress increases. This is because large inelastic deformation concentrated in the peak stress part or at weak sectional part if the stress distributes with severe gradient for high-strength steels, whereas the plain strength steel SS400 had good property to redistribute the inelastic deformation throughout the entire specimen.

INELASTIC STRAIN DISTRIBUTION

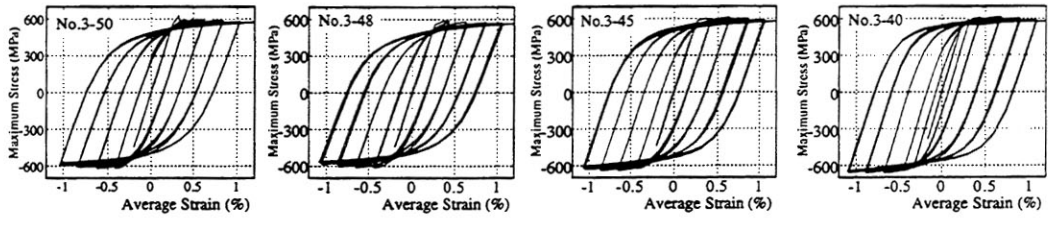
In order to investigate the inelastic strain distribution throughout the test specimen, we measured the axial strains at 5 sections on both sides of specimen. Considering the symmetry about the span center of test specimen, strains were measured only at the upper half part of specimen. The obtained strain distribution are illustrated in Figs. 6(a)~(e). The lateral axes show the measured strain and the vertical axes show the measuring positions which are shown in the left hand figures. The percentage values in the figures show the controlled level of axial elongation deformation. The measured strains, of course, increase when the level of elongation deformation increases.



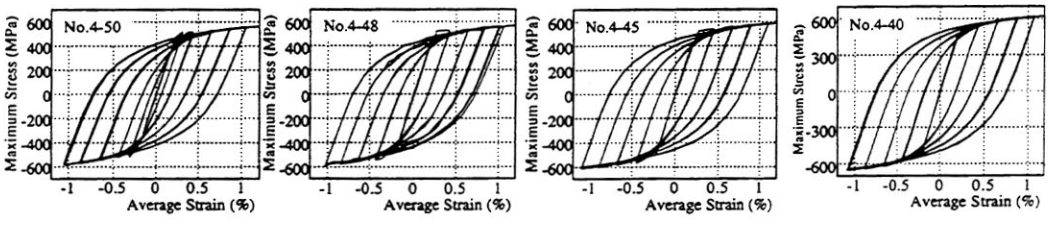
(a) WT780 steel



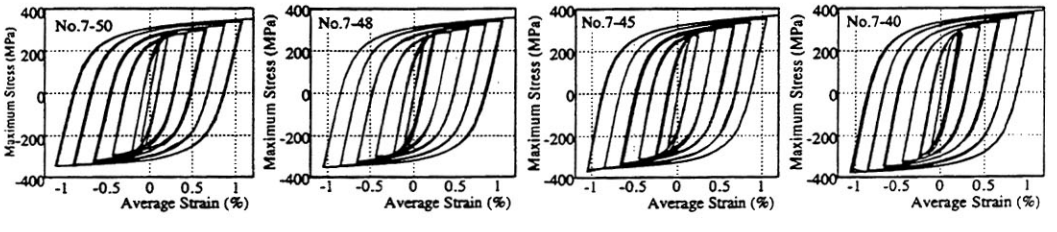
(b) M-WT780 steel



(c) WT590 steel



(d) M-WT590 steel



(e) SS400 steel

Fig. 5 Hysteresis of stress and average strain

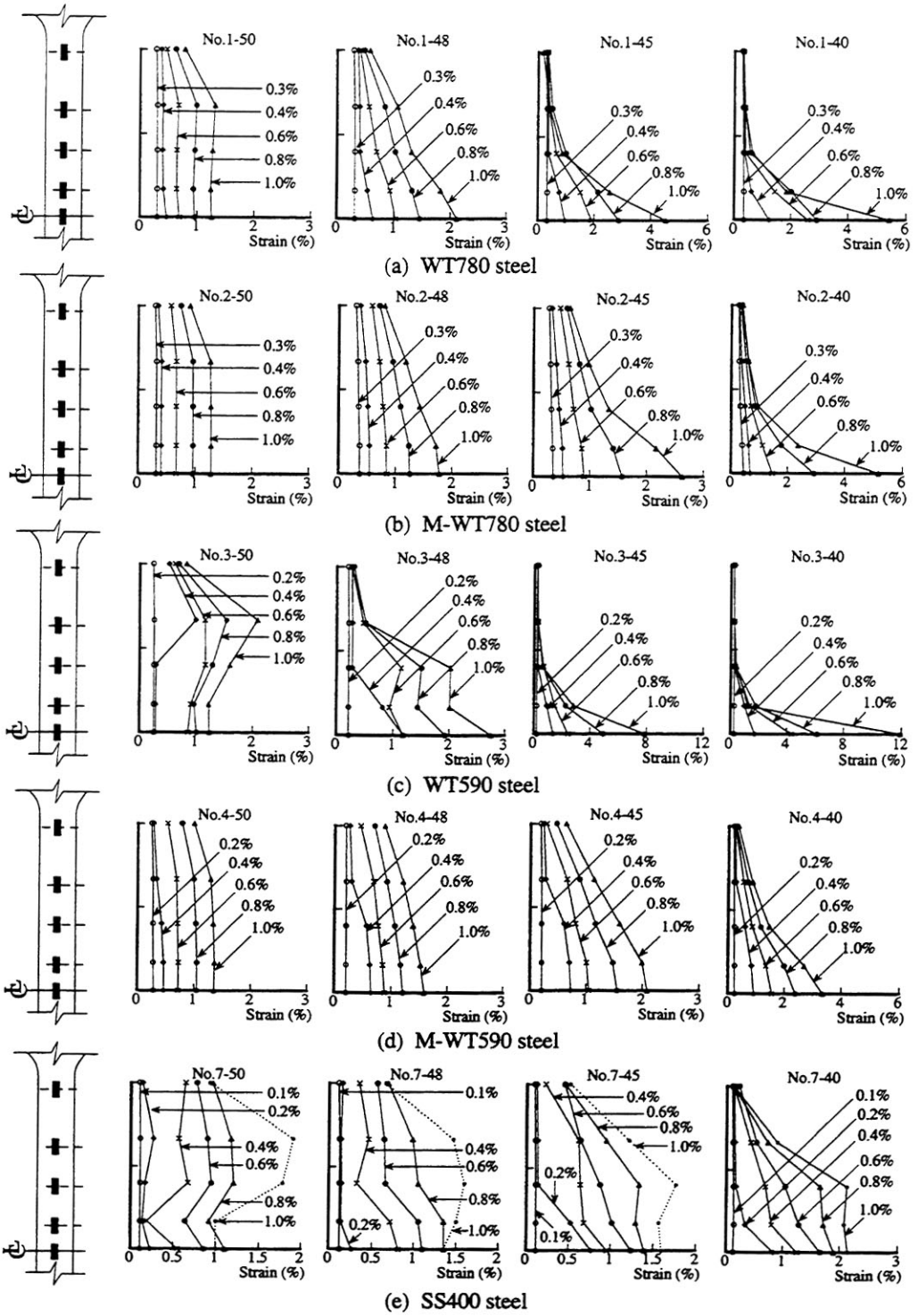


Fig. 6 Measured strain distributions in specimens

It is seen from Figs. 6(a)~(e) that the strains of the straight specimens (with 50mm center width) are approximately distributed in the uniform shape. As the gradient of the sectional variation increases, the inelastic deformation or strain is concentrated largely in the weak section part. The extent of strain concentration of plain high-strength steels (WT780, WT590) is more severe than that of modified high-strength steels (M-WT780, M-WT590).

STRAIN CONCENTRATION AT HIGH STRESS PART

The strain concentration ratio at high stress part (center of the specimens) is shown in Figs. 7(a)~(e). Strain concentration ratio is defined as the ratio of measured strain at the center section of specimens over the average strain. It is noted that the meaning of each axis in Figs. 7(b)~(e) is the same as that shown in Fig. 7(a).

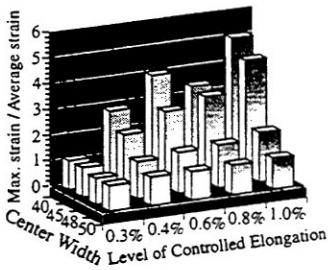
Considered from the steel categories, the strain concentration ratio of high-strength steels is higher than that of plain strength steel SS400; plain high-strength steel (WT590) is higher than that of modified high-strength steel (M-WT590). This is because the yield ratio of plain strength steel SS400 is lower than that of high-strength steels, and that of modified high-strength steels (M-WT590) is lower than plain high-strength steel (WT590). Steels with a low yield ratio can redistribute more easily the inelastic deformation from high stress areas to the low stress areas than the steels with a high yield ratio.

From the influence of gradient stress, the greater the extent of gradient stress is, the higher the strain concentration ratio. It is known that the greatest strain concentration ratio for high-strength steels (seen from Figs. 7(a)~(d)) occurs in test specimens with the greatest gradient stress (with 40mm center width) and at the maximum controlled level of elongation deformation (1.0%). In other words, strain concentration ratio increases with the extent of gradient stress and as the deformation level increases. However, the greatest inelastic strain concentration of plain strength steel SS400 (seen from Fig. 7(e)) occurs in the specimen with the greatest gradient stress and at the initial stage when axial elongation level is 0.2%; with the deformation level increases, the inelastic strain concentration ratio decreases.

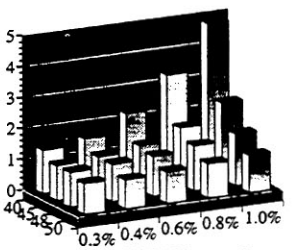
INELASTIC DEFORMATION CAPACITY

The inelastic deformation capacity (denoted as IDC simply hereafter) of the steels is shown in Fig. 8. The average strains at maximum load and at rupture are used to express the inelastic deformation capacity of the steels. 'Mono' in Fig. 8 represents the results obtained from the monotonous tension loading test.

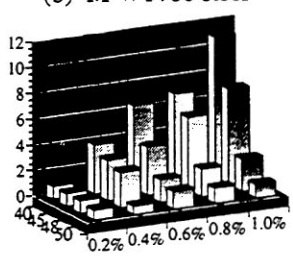
Some observations from Fig. 8 can be stated as following: i) IDC of steels under cyclic loading is lower than that under monotonous loading; ii) IDC of high-strength steels is lower than that of plain strength steel SS400; iii) IDC of steels decreases when the gradient of stress increases; iv) IDC of modified high-strength steels (M-WT780 and M-WT590) is larger than that of plain high-strength steels (WT780 and WT590); v) For modified high-strength steels and SS400 steel, the average strain at maximum loading has a great part of the entire deformation at rupture; whereas, for WT780 and WT590 steels, the



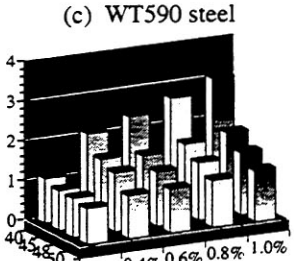
(a) WT780 steel



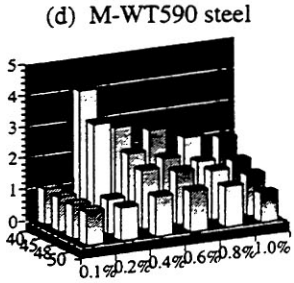
(b) M-WT780 steel



(c) WT590 steel



(d) M-WT590 steel



(e) SS400 steel

Fig. 7 Strain concentration ratio at center of specimens

average strain at maximum load has only a small part of entire deformation until rupture.

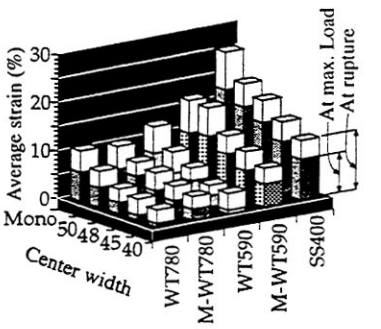


Fig. 8 Inelastic deformation capacity

CONCLUSIONS

Even though the high-strength steels have not been permitted to be used in the seismic designed structures by current Japanese building laws, if their large elastic deformation capacity is effectively used through the combination with the extra-low-strength steels, some more rational seismic design methodologies could be certainly constructed. In order to investigate the inelastic mechanical properties of high strength steels when it enters inelastic range under an extreme earthquake excitation, a series of cyclic loading experiments for various kinds of steels have been carried out under 4 kinds of different gradient stress. The following conclusions can be obtained from the experiment.

1) None of test specimens was observed to be broken or cracked during the cyclic loading experiment even as the elongation deformation level reached -1% or 1%. It can be said that the high-strength steels can be used in the earthquake-resistant building structures provided that it is used in the elastic range and if there is no problem with regard to welding.

2) Gradient stress will reduce the inelastic deformation capacity significantly for all kinds of steels since the gradient stress will cause strain concentration at weak sections. As the strength of steels increases, the strain concentration in weak section becomes more severe. If the gradient of stress reaches 80%, about half of inelastic deformation capacity will be reduced.

3) Gradient stress has no influence on the ultimate strength of high-strength steels. However, it will increase the ultimate strength for plain strength steel SS400.

4) The inelastic strength of high-strength steels will decrease with the number of cyclic loading increases.

5) Modified high-strength steels have better inelastic deformation capacity than that of plain high-strength steels.

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