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INELASTIC BEHAVIOR OF HIGH STRENGTH STEELS WITH WELD CONNECTIONS UNDER CYCLIC GRADIENT STRESS

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ABSTRACT

This paper presents a number of results of cyclic loading experiments of high strength steels with weld connections. Four kinds of different steels whose tensile strength are 780MPa, 590MPa, 490MPa and 400MPa respectively and two kinds of modified 600MPa and 800MPa class high strength steels whose yield ratio is lower than that of general high strength steels are used. Specimens with two type weld connections and with tapered sections have been considered so that the gradient stress in a actual structural beam and the welding effect between columns and beams can be simulated in the experiments. Compared to the experimental results of high strength steels without weld connections, inelastic deformation capacity is dramatically reduced due to the influence of weld connections. It is also found that strong columns connected to the beams through welding have great restricting influence on the development of inelastic deformation at beam-ends. It is concluded from the experiments that high strength steels whose strength is more than 600MPa should be used in seismic structures by using their large elastic deformation capacity instead of inelastic deformation capacity.

KEYWORDS

High strength steel, Weld connection, Cyclic loading experiment, Gradient stress

INTRODUCTION

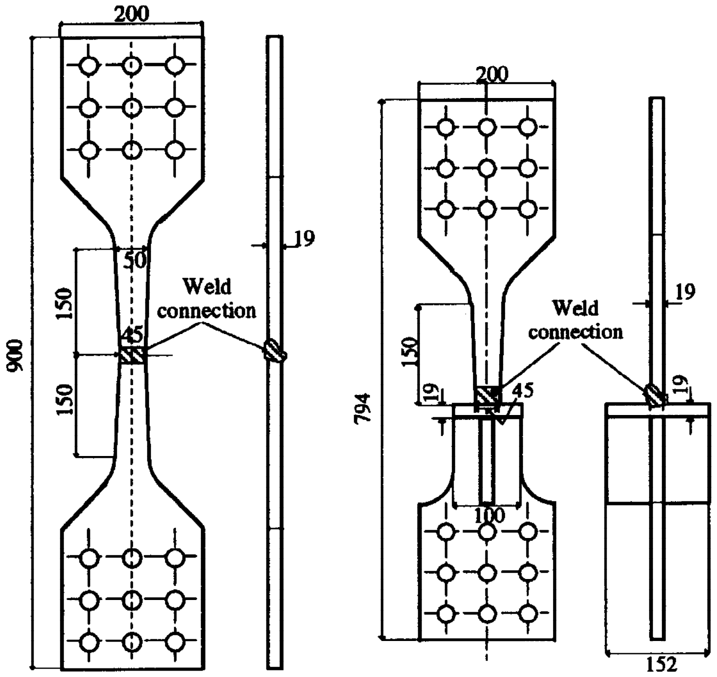
In the long history of mankind, humans managed to build shelters to protect themselves against natural disasters, such as heavy rain and flood, tornadoes and strong wind, as well as large earthquakes, etc. Buildings as one kind of shelters is developed and improved constantly by mankind during their struggles to the natural disasters. It is well known that building materials have been made great progress from the soil, stone, brick, straw and wood in the ancient times to the concrete, steel and many new chemical materials at present. However, humans cannot still escape the threat of earthquakes even in today when the science and technology is so highly developed. For example, during the famous Northridge earthquake happened in USA on Jannuary 17 1994, and the well known great Hyogo-ken Nanbu earthquake of Japan happened in Jannuary 17 1995, there was a great loss of human life and economic disruption arisen since many civil engineering projects and building structures as well as facilities were destroyed.

Traditional approaches of structural seismic design require that the structures should have enough inelastic deformation capacity to absorb the earthquake energy. High-strength steels therefore could not be used in the building structures located in the earthquake active areas according to the current building's law since high strength steels lack sufficient inelastic deformation capacity due to their high yield ratio (yield point strength over ultimate strength) and welding problem. However, if some energy dissipation system (hysteretic damping system, viscous damping system or combining with the active control system) is incorporated in the building structures, high-strength steels whose elastic deformation capacity is double or trible larger than that of plain strength steels such as SS400 can be used in the primary structures of a building on the basis of the concept of energy based structural design (Akiyama 1985, Connor, Wada and Iwata 1992) provided that the primary structure is designed in the elastic range.

The critical problem of steel structures especially for high-strength steels during earthquake excitation is lack of ductility in the beam-ends where there is high level gradient stress and weld connections. During the Northridge earthquake of USA and the great Hyogoken-Nanbu earthquake of Japan, many severe failures were observed in steel structures originated from the cracks at the fillet weld connections between beams and columns (Krawinkler 1994, Naeim et al., 1995 and Steel Committee 1995). Aoki et al. (1982) and Kato (1990) studied the inelastic deformation capacity considered the influence of different yield ratio and gradient stress by using small tapered specimens. Many other researchers such as Yamashita et al. (1993), Iwata and Wada et al. (1992,1993) made a lot of experimental researchs for the high strength steels. Morita et al., (1994) studied the mechanical properties of welded joint between low-yield ratio 600MPa class high strength steel members. There was no researchs so far to study the inelastic mechanical properties of more than 600MPa class high strength steels with weld connections under cyclic gradient stress. Although we here assume the high strength steels to be used in the elastic range, it is necessary to investigate the inelastic behaviors of high strength steels under cyclic loading to consider in case of encountering unexpect extreme large earthquake. This paper presents the results of a series of cyclic loading experiments using high strength steel specimens with weld connections and tapered sections.

OUTLINES OF EXPERIMENTS

A series of similar cyclic loading experiments using high strength steels without any weld connections have been carried out by the authors. The outlines of the experiments can be referenced in the papers of Huang et al.,. (1995). In this experiment, two types of test specimens shown in Fig. 1 as well as in Photo 1 and 2 are used. The thicknesses of steel plate of both type A and type C specimens are 19mm that is usually used



(a) Type A (b) Type C

Fig. 1 Outlines of specimens

Table 1 Mechanical properties of the steels

Steel	Yield strength (MPa)	Yield ratio (%)	Elongation ratio (%)
SS400	281	63	25
SM490	355	67	23
HT590	593	91	13
HT780	802	93	10
M-HT590	523	75	17
M-HT780	702	83	10

Table 2 Test specimens

Steels	Type A	Type C
SS400	AT-400	CTS-400
SM490	AT-490	CTS-490
HT590	AT-590	CTS-590
HT780	AT-780	CTS-780
M-HT590	AT-M590	CTS-M590
M-HT780	AT-M780	CTS-M780

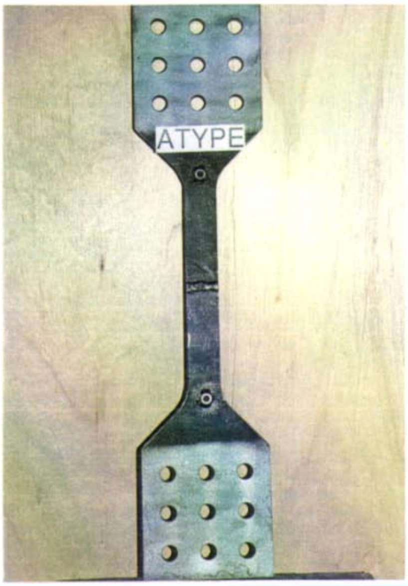


Photo 1 Type A specimen

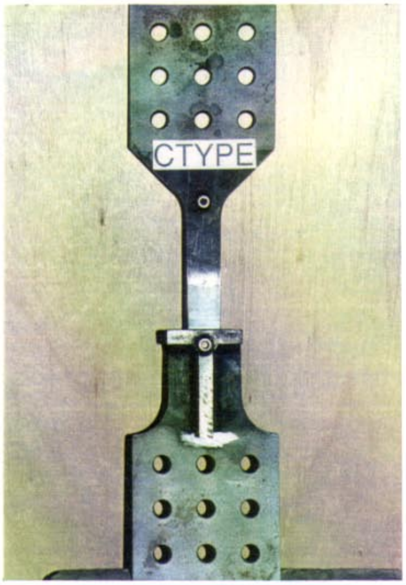


Photo 2 Type C specimen

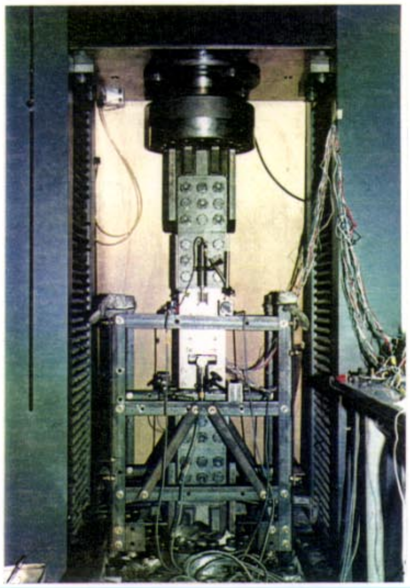


Photo 3 Instalation of experiments

thickness in the real building structures. Type A is symmetrized upper and lower about the weld connection located in the center position. Test part length of type C specimen is shorter than type A. The lower part of type C specimen is aimed to simulate the restricting influence of columns on the inelastic deformation at beam-ends. Test part lengths are 300mm for type A and 150mm for type C specimens. The end width is 50mm and the central width in weld connection position is 45mm for both type A and type C specimens which will produce 90% gradient stress.

Mechanical properties of the steels used in the experiments are listed in Table 1. SS400 and SM490 are plain strength steels, HT590 and HT780 are general 600MPa and 800MPa class high strength steels. M-HT590 and M-HT780 are modified 600MPa and 800MPa class high strength steels whose yield ratio are lower than those of general high strength steels HT590 and HT780. The names of the test specimens are introduced in Table 2 whose first character A and C stand for the specimen types; second character T means the specimen has tapered section; third character S of type C specimens means that the steels used in beams and columns are the same. Cyclic loading experiments with equal amplitude compression and tension are carried out in Research Laboratory of Engineering Materials (T.I.T) under a large test machine AG-150TD which is so stiff that the loading can be controlled by the measured displacement. The installation of the specimen to the test machine is shown in Photo 3.

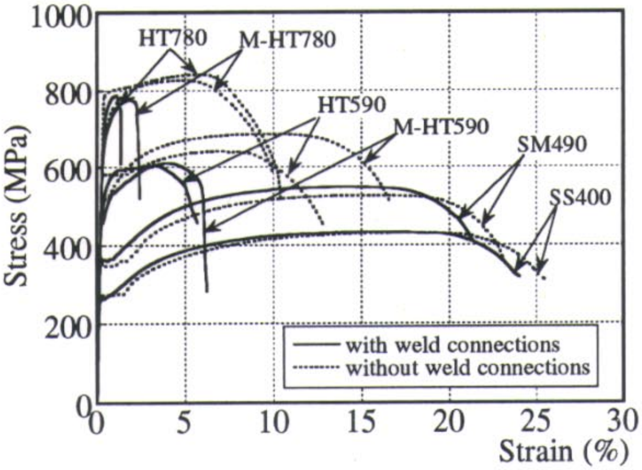


Fig. 2 Global relationship of stress and strain obtained from monotonous tensile loading test

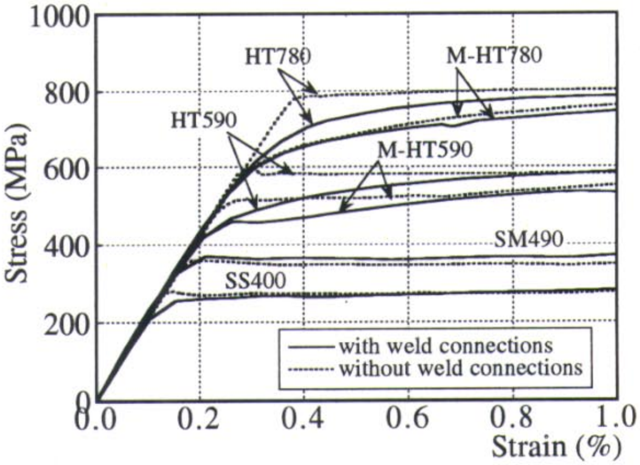


Fig. 3 Local expension of Fig. 2 with 1.0% range

MONOTONOUS TESILE LOADING TEST

We first use type A specimens without gradient stress (using parallel section specimens) for each kind of steels to carry out monotonous tensile loading test. The obtained relationships between stress and average strain are shown in Figs. 2 and 3. The results without weld connections carried out by Huang (1995) are also illustrated in the figures for the purpose of comparison. Fig. 2 shows the global relations and Fig. 3 shows the local expansions within 1.0% average strain. It is found that weld connection has no great influence on the inelastic deformation capacity for general strength steels SS400 and SM490. However, for high strength steels HT590 and HT780 or for modified high strength steels M-HT590 and M-HT780, inelastic deformation capacity is dramatically reduced if the specimens include weld connections. The ultimate strengths of high strength steels are also reduced some more. It can be concluded from these experimental results that the primary factor of effecting the inelastic deformation capacity of high strength steels is mainly welding problem instead of traditionally mentioned "yield ratio". Therefore, we would emphasize that the high strength steels should be used by the advantage with large elastic deformation capacity rather than the inelastic deformation capacity because of the influence of weld connections.

CYCLIC LOADING TEST

Loading Cycles Cyclic loading is carried out until the axial deformation reaches 1.0%L and then loads monotonously in tension until the specimen is ruptured. Fig. 4 shows the loading cycles controlled by the measured deformation where L stands for the test part length of specimens.

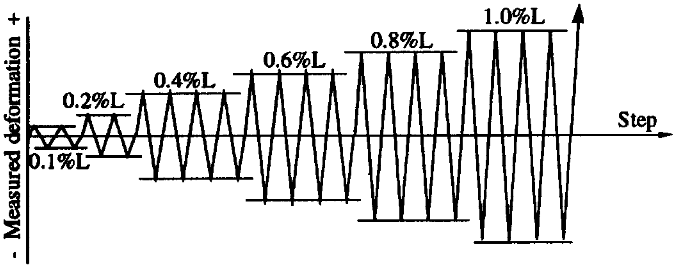
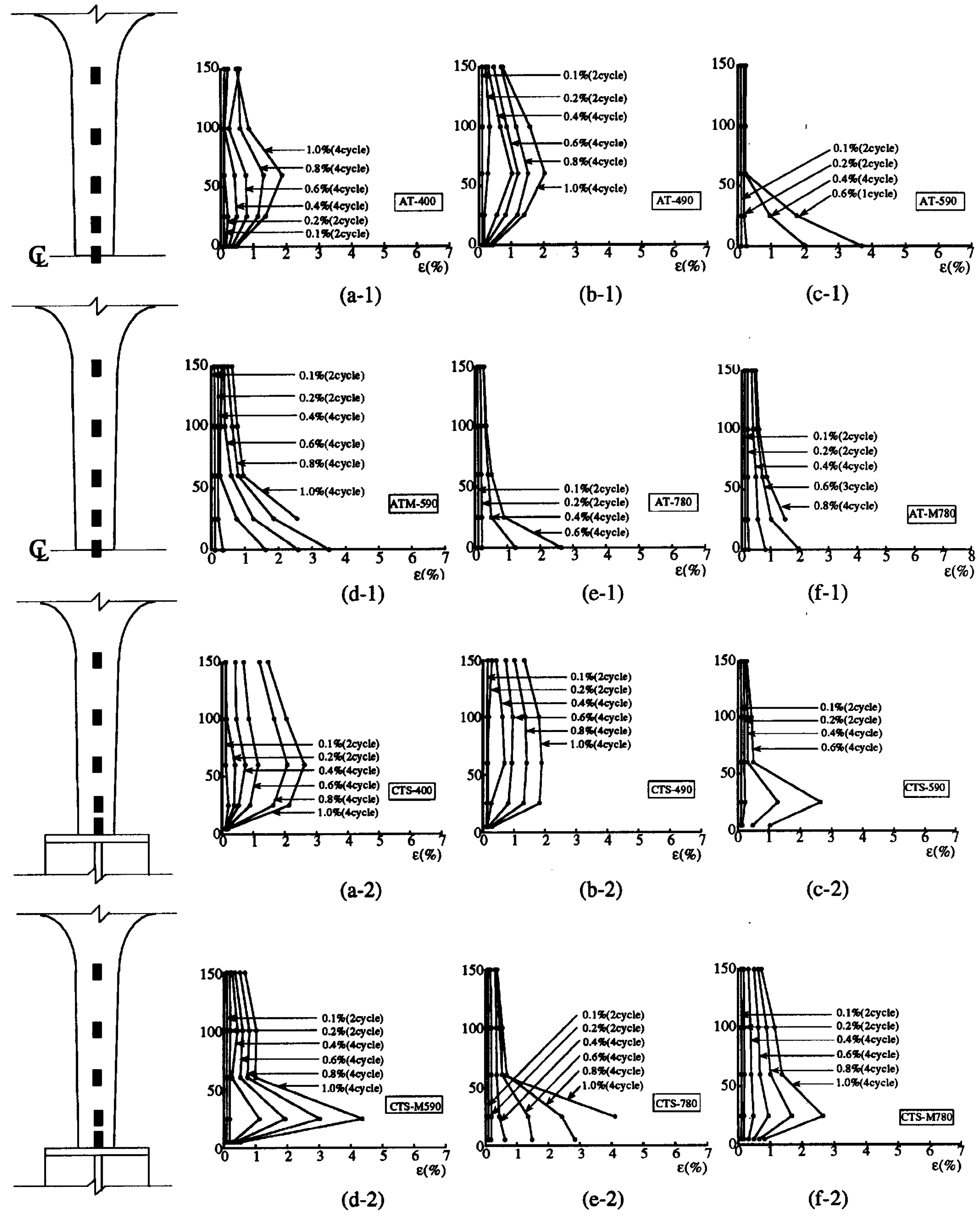


Fig. 4 Loading cycles controlled by the measured deformation

Measured Strain Distribution The measured strain distribution along with the axial direction of specimens are illustrated in Fig. 5. Figs. (a-1) to (f-1) show the results of type A specimens and Figs. (a-2) to (f-2) show the results of type C specimens. The vertical axes of the figures show the measuring positions of the strain. The percentage values in the figures show the deformation level used to control loading cycles same as those shown in Fig. 4. The number of cycles in the parenthesis of the figures show that at which cycle the strain are measured. Seeing from the results of type A specimen, the measured strain at welding part is smaller than those measured from base metal for SS400 and SM490 steels. Otherwise, the measured strain at welding part is larger than those measured from base metal for both general high strength steels HT590 and HT780 as well as for modified high strength steels M-HT590 and M-HT780. It is made clear by the results of welding metal test that the yield strength of welding metal is higher than that of base metal for SS400 and SM490 steel specimens, but lower for high strength steels HT590 and HT780 specimens. Seeing from the results of type C specimens, the measured strain in welding part is less than those measured from base metal for both general strength steels SS400 and SM490 and high strength steels HT590 and HT780. It is also found that column member has large restricting influence on the development of weld connections to the beams.

Hysteretic Relations of Stress and Strain The hysteretic relationships of stress and strain obtained from the cyclic loading experiments are shown in Fig. 6. Label "Average strain" of lateral axes in the figures means the measured axial elongation divided by the test part length of specimens. "Measured strain at weld" means the actually measured strain by gages at the welding positions. It is found that the strain measured in the welding positions especially for type C specimens is not progressed largely for SS400 and SM490 steels, but it increases greatly with the increase of deformation level used to control loading cycles for the high strength steels HT590, HT780, M-HT590 and M-HT780. This is because that the strength of welding metal used for high strength steels are lower than that of base metals. Another point should be mentioned is that axial elongation deformation of type A specimens is larger than that of type C specimens even the loading control levels are the same because the test part length of type A is longer than that of type C specimen. Therefore, strain at welding positions must be larger than those of base metal for the high strength steels which are more difficult to redistribute the inelastic deformation than plain strength steels SS400 and SM490. It means that strain concentrates in the welding positions more severely for high strength steels than for plain strength steels SS400 and SM490.

Broken Sections Photos 4 (a-1) to (c-4) show the broken sections of failured specimens after the experiments finished. It is found that HT780 amd M-HT780 steel is brittle failured without large residual inelastic deformation



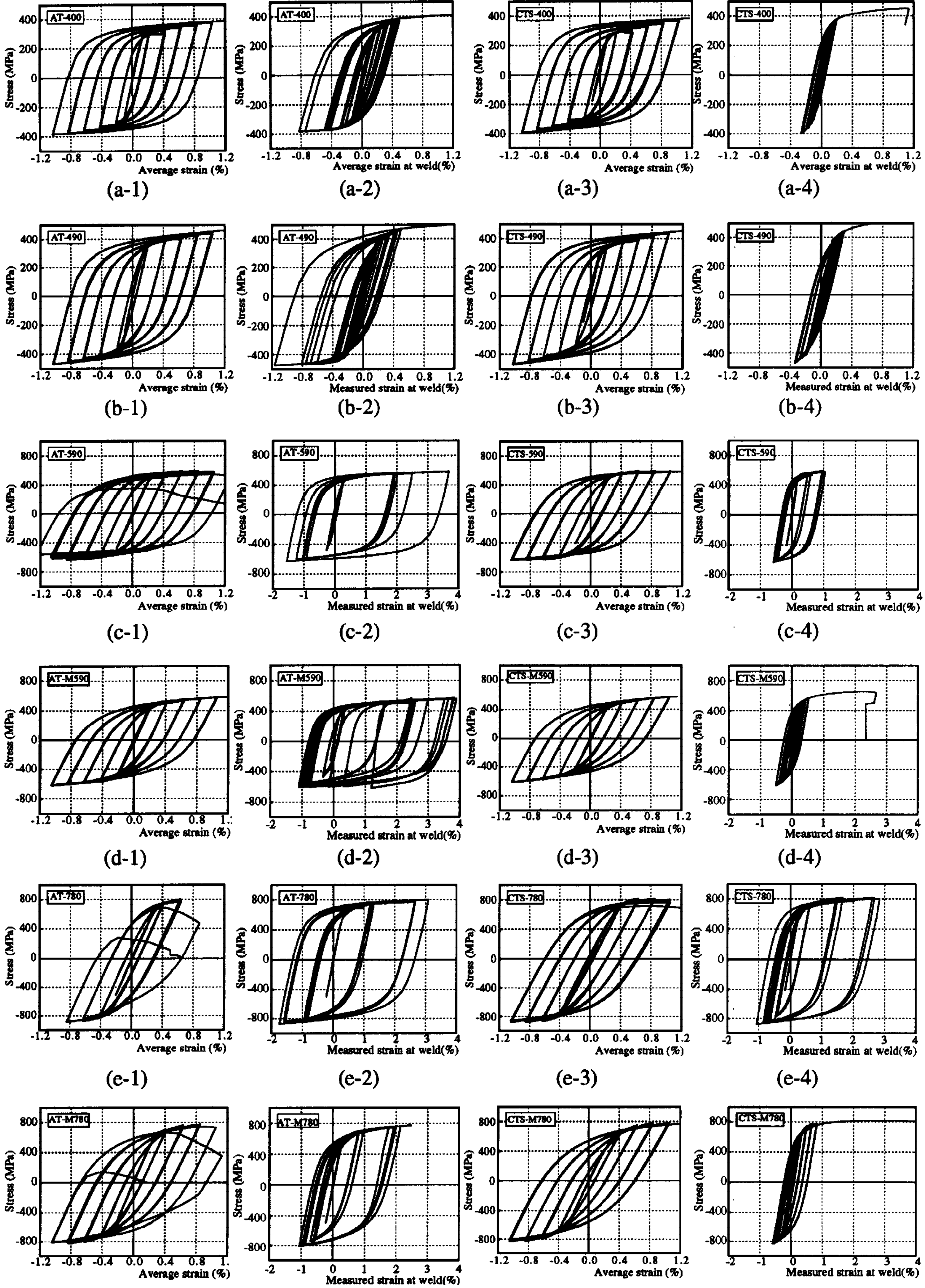
(a-1) (b-1) (c-1)

(d-1) (e-1) (f-1)

(a-2) (b-2) (c-2)

(d-2) (e-2) (f-2)

Fig. 5 Distribution of measured strain in axial direction of specimens



(a-1) (a-2) (a-3) (a-4)

(b-1) (b-2) (b-3) (b-4)

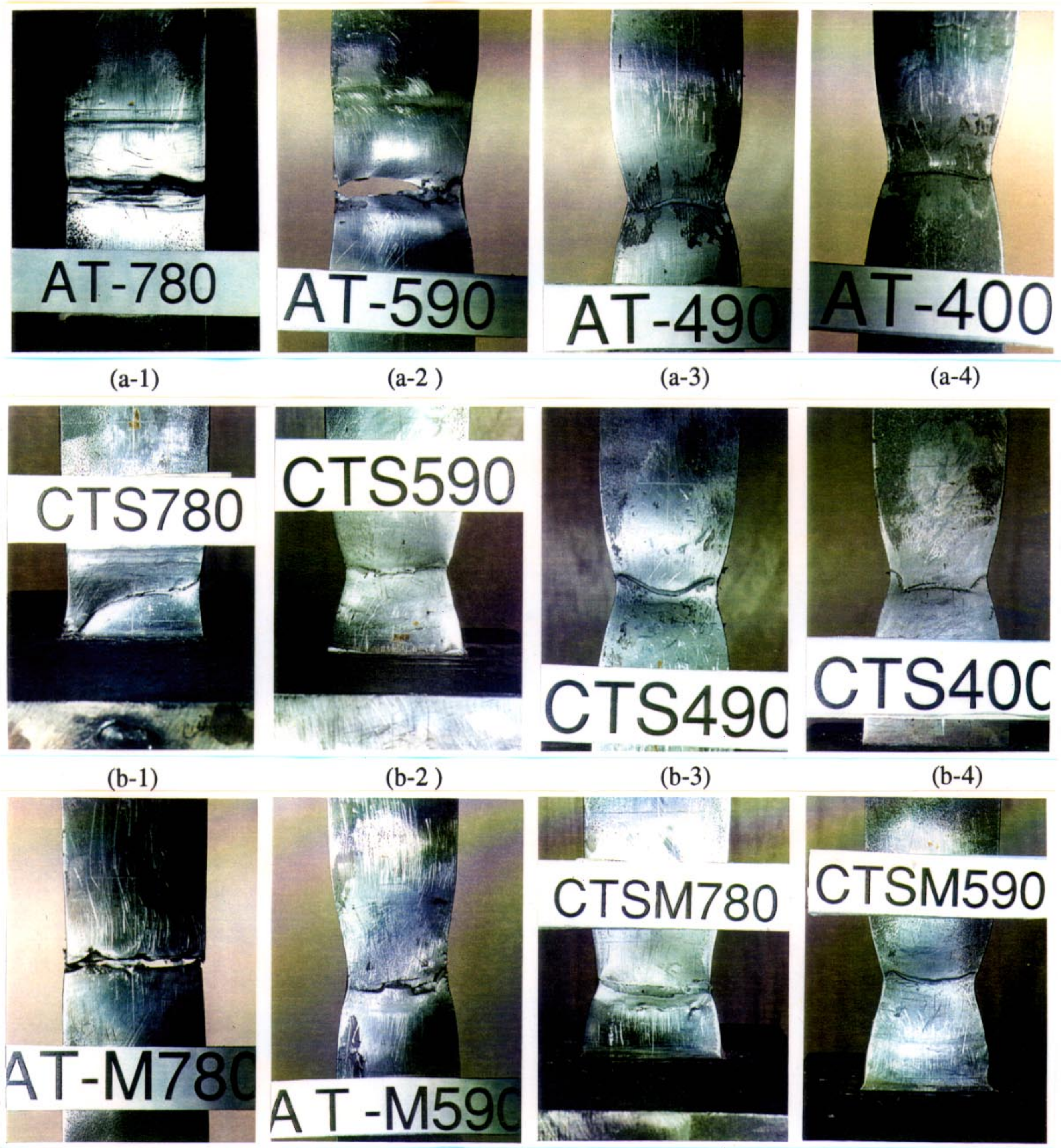
(c-1) (c-2) (c-3) (c-4)

(d-1) (d-2) (d-3) (d-4)

(e-1) (e-2) (e-3) (e-4)

(f-1) (f-2) (f-3) (f-4)

Fig. 6 Hysteretic relations between measured stress and strain



(a-1) (a-2) (a-3) (a-4)

(b-1) (b-2) (b-3) (b-4)

(c-1) (c-2) (c-3) (c-4)

Photo 4 Details of broken sections

in type A specimens. Other test specimens are failured after they experience large inelastic deformation especially for SS400 and SM490 steels. Almost test specimens are failured in the heat influenced part of base metal except for CTS780 which is failured of the crack starting from the fillet weld connection.

CONCLUSIONS

High strength steels are assumed to be used in the elastic range. It is necessary to investigate their inelastic behavior under cyclic loading to consider the case of encountering unexpect extreme large earthquake. In this paper, we have presented the results of cyclic loading experiments using 6 kinds different steels whose strengths range from 400MPa to 800MPa. Following conclusions can be obtained from the experiments.

(1) Although weld connection has no influence on the loading capacity and inelastic deformation capacity for plain strength steels SS400 and SM490, weld connection will dramatically reduce the inelastic deformation capacity for the high strength steels HT590, HT780 and even for modified high strength steels M-HT590 and M-HT780 whose yield ratio are less than those of HT590 and HT780.

(2) It is obvious that the primary factor to influence the inelastic deformation capacity of high strength steels is weld problem instead of yield ratio. It is difficult for the high strength steels to be used in large inelastic deformation range.

(3) In the weld connections between columns and beams, strong columns will restrict in great extent the development of inelastic deformation at the beam-ends.

(4) Type A specimens of general high strength steels HT590, HT780 and M-HT780 failured before they finish 1%L cycle loading. It means that high strength steels with weld connections can not absorb sufficient earthquake energy if they are used in the seismic designed structures.

(5) On the contrary to the general strength steels SS400 and SM490, high strength steels whose strengths are more than 600MPa have the characteristics with large elastic deformation capacity and lack of inelastic deformation capacity. Therefore, high strength steels should be used in the seismic designed structures by their large elastic deformation capacity instead of inelastic deformation capacity.

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