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SINGLE OR FEW EXCURSION FAILURE OF STEEL STRUCTURAL JOINTS DUE TO IMPULSIVE SHOCKS IN THE 1995 HYOGOKEN NAMBU EARTHQUAKE

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ABSTRACT

Numerous steel structural buildings were severely damaged, collapsed or overturned due to the 1995 Hyogoken Nambu Earthquake. It has been observed that beam flanges close to the welded beam-to-column connections or the welded zones at the connections, in the moment resisting frames, were brittlely fractured. In order to make clear the main cause of the structural damage of steel buildings, the first part of this paper describes the phenomenon of the impact failure of the welded joints derived from an experimental investigation. The result of the experiment has shown the significant decrease of yield ratio under high speed loading condition, because the yield strength increases drastically, compared with the growth of the tensile strength. The remainder of this paper refers to dynamic response characteristics of typical steel frames subjected to both horizontal and vertical ground motions. From the result of analysis, it can be explained that the single and/or few excursion failure at the joint could occur due to the high strain rate.

KEYWORDS

Steel structural joints; effect of strain rate; yield ratio; dynamic analysis; effect of vertical ground motion.

INTRODUCTION

On 17th of January 1995, a great earthquake hit the Southern Hyogo Prefecture in Japan. Around the center of Kobe City, numerous steel structural buildings were severely damaged, collapsed or overturned. Among the damaged steel structures, it has been observed that beam flanges close to the welded beam-to-column connections or the welded zones at the connections were brittlely fractured. Soon after the earthquake, it was quite difficult to find out the existence of structural damage, because any distinctive story drifts or significant damage of exterior walls had not been observed. Furthermore, the characteristics of the earthquake can be summarized as follows: The duration time of the earthquake is so short as about 10 minutes, and the ground acceleration level of horizontal component as well as the level of vertical component is quite high. From the characteristics of the ground motion of the earthquake and the actual damage of the structures, it has been recognized that the joints may suffer the impulsive force and the simultaneous action of both horizontal and vertical ground motions on the structures may result in single or few excursion failure of the joints.

The former suggests the necessity to clarify how the mechanical properties of the joints can be affected by strain rate. For this reason, an experimental investigation on the effect of strain rate will be reviewed for typical butt welded joints subjected to monotonic high speed tensile loading, and the effect of strain rate on the yield ratio will be discussed in comparison with the effect in the case of the base metal.

The structural damage due to the latter effect, that is, the damage caused by the simultaneous action of both horizontal and vertical ground motions, can be assessed by applying so-called large deflection elasto-plastic analytical method to the dynamic analysis of the moment resisting frames(Kaneta *et al.*, 1982). Analytical result of one-bay, one-storied steel frames subjected to the 1995 Hyogoken Nambu Earthquake, will be presented. From the result, it will be seen that the stress-strain response at the critical sections of the beam ends can be significantly influenced by the existence of the vertical ground acceleration and strain drift at the points can progress remarkably as if the structures would be loaded monotonically and/or few cyclic strain reversals with large amount of plastic strain range, accompanied with high strain rate. Such phenomena may lead the structures to come to collapse without enough time for vibrating cyclically beyond the elastic range to absorb the great amount of input energy due to the earthquake.

HIGH SPEED TENSILE LOADING TEST

Experimental Procedure

A special loading apparatus was prepared in order to apply high speed tensile load to mild base metal and the butt welded joint. The apparatus as shown in Fig. 1, was composed of flywheel, crank, loading arm and mounting device for the specimen. The apparatus was operated so that the tensile load was applied to the bottoms of the specimens suspended from the reaction frame, with the lever by engaging the cam while using the clutch, after the rotating speeds of the flywheel were controlled at the selected constant values between 350 to 1500 r.p.m.. As shown in Fig. 2, the specimens were suspended from the beam of the reaction frame, through the universal joint and the load transducer. The load and the deflection between the marked points of the specimens were detected and the values were recorded to a data acquisition system throughout the experiment. In this testing method, the test was conducted under the condition with constant rotating speed of the flywheel. This means that the strain rate beyond yielding may differ from the rate within the elastic limit of the material. However, since the average elongation rate after yielding, calculated from the deflection outputs measured by the extensometers between the marked points, was kept constant for each selected rotating speed of the flywheel, the average elongation rate was regarded as strain rate beyond yielding.

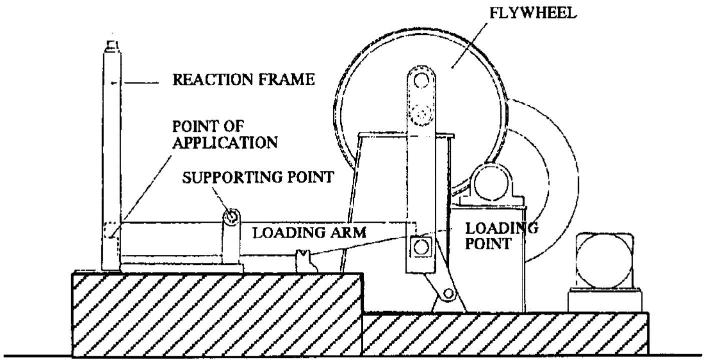

Fig. 1. Loading apparatus

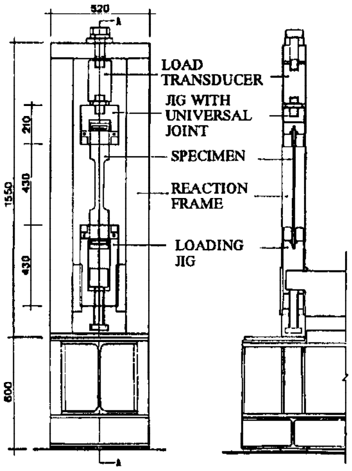

Fig. 2. Specimen setup (unit: mm)

Specimen

2 types of the specimens were used for the high speed tensile loading test. The base metal specimen was made of JIS SS400 4.5 mm thick mild steel plate, and was shaped as shown in Fig.3. The butt welded joint specimen was made of identical grade steel plate to the base metal specimen. The joint specimen was fabricated by I grooved CO_2 shielded arc welding with bucking plate. The root gap was 2 mm for the specimen. The bucking plate was scraped and removed after welding, in order to shape the specimen. Projection plates at the ends of the specimen as shown in Fig.3 , were welded to set up the specimen to the loading jig. The specimen with identical shape and the size to Fig.3 was also used for static tensile test.

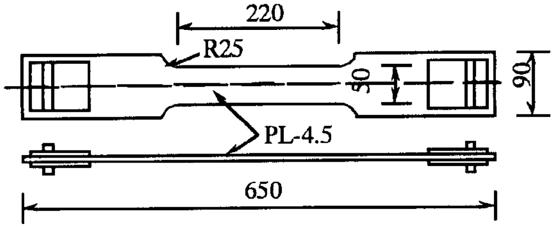

Fig. 3. Specimen used for monotonic tensile loading test

RESULT OF EXPERIMENT

In order to compare the experimental result of the butt welded joint with the result of the base metal, the effect of strain rate on the lower yield point and the tensile strength was examined as shown in Figs. 4 and 5, respectively. In the figures, the ordinates are normalized by dividing the original values by the static lower yield point and the ultimate strength of the base metal. From the figures, it can be seen that the remarkable progress of yield point of the butt welded joint is observed, whereas the ultimate strength of the joint is not sensitive to strain rate. This means that yield ratio of the butt welded joint is sensitively affected by the strain rate.

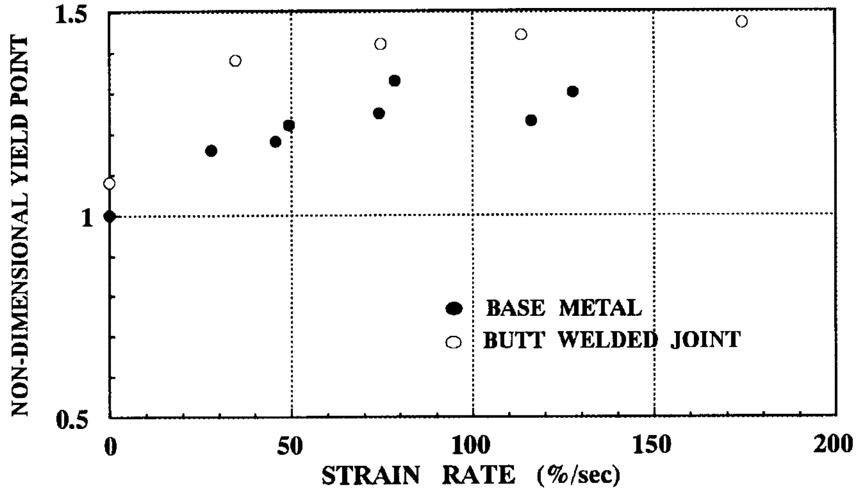

Fig. 4. Effect of strain rate on yield strength of base metal and the butt welded joint

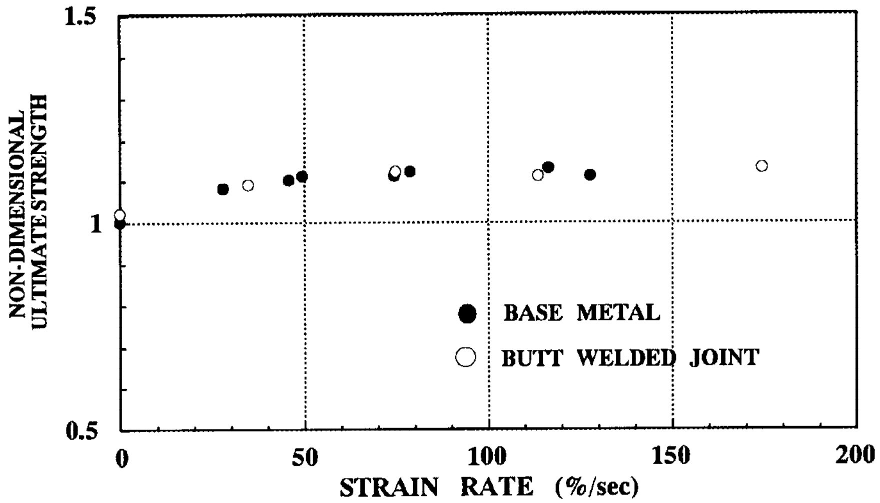

Fig. 5. Effect of strain rate on the ultimate strength of base metal and the welded joint

DYNAMIC ANALYSIS OF STEEL FRAME

Design of Frame

The one-bay,one-storied rigid frames designed for the dynamic analysis were assumed to be constructed in the following manner. The members consisted of wide flange sections made of JIS SS400 mild steel, and columns were rigidly fixed at the bottoms to the foundation and connected at the tops to the beams by welding. All members were adequately braced and/or stiffened against lateral, torsional and local buckling behavior.
The members were designed so that inelastic behavior is limited only in the beams, while the columns remain within the elastic range. That is, the frames were designed as weak-beam, strong-column structures.

In order to proportion each member, two types of loads were statically applied to the frames, namely, dead and live loads as gravity load, and the horizontal seismic load. The gravity load was $0.5 t/cm^2$ and it was distributed along the beams. The horizontal seismic load was applied at the floor level in the magnitude 0.2 as the seismic shear coefficient. The sum of the bending moments at the ends of the beams due to both gravity and horizontal loads was computed. The plastic section moduli of the beams were determined by dividing the plastic moment by the yield stress, when the values were equalized to the fully plastic moment. Two frame models, named as Frame 1 and 2 , were designed by employing the same procedure described above, but the span length of Frame 2 was varied as twice as the length of Frame 1.

Dynamic Model

In order to simulate the dynamic behavior of the steel frames subjected to both horizontal and vertical ground accelerations, as well as gravity load, three lumped masses were assumed. Two of them were located at the tops of the columns and named as mc, and the mass mg was located at the center of the beam, for each model, as shown in Fig. 6. The ratio of mass, m', which was defined as the ratio, mg/mc, was determined as a constant value, 2.0. The natural periods of vibration of the models were computed by employing the Householder method. Their fundamental periods of vibration of the horizontal and vertical floor modes are summarized in Table 1.

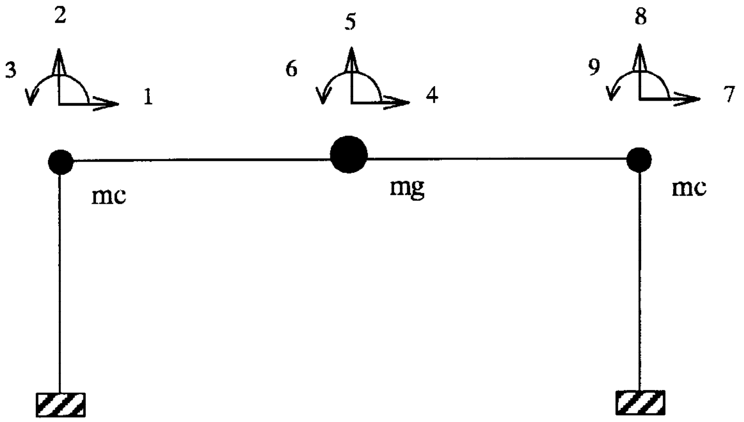

Fig. 6. Dynamic Model used for the Analysis

Table 1. Dynamic Characteristics of Frames

	Frame 1	Frame 2
Natural Period (Horizontal) (sec)	0.36	0.31
Natural Period (Vertical) (sec)	0.16	0.27

Beam Element and stress-strain relation

The beam, as one member, was subdivided into many elements in order to examine the stress-strain behaviors at or near the end of the beam and its midspan, as would be able to apply to the dynamic large-deflection analysis of steel frames. Each element of the beam was assumed to consist of two concentrated masses which were separated from each other by a distance of twice the radius of gyration of area, so as to be idealized as an equivalent sandwich section.

The stress-strain relation of the element was assumed as bi and tri linear model, which had been derived from the experimental result concerning with beam-to-column welded joint under static loading condition(Kaneta and Kohzu, 1980). In the adopting stress-strain model, the virgin loading state and the subsequent cyclic reversed loading state are precisely separated. At the virgin loading state, the relation is approximately divided into tri-linear model which consists of elastic range, plastic flow range and strain hardening range. After unloading in the inelastic range, let the reloading apply in the opposite direction to the initial-state, then the stress-strain relation can be approximated using a bi-linear skeleton curve and the amount of absorbed energy at the steady-state. The relation between the absorbing energy per cycle and the plastic strain amplitude can be formulated as an exponential equation.

Thus, the hysteresis loop can be traced in the following way. Let the absorbing energy per cycle stand for the area surrounded by a modified bi-linear hysteresis loop which is composed of an elastic stiffness that is equivalent to the initial stiffness, and of a characteristic secondary stiffness terminated at some point on the upper or lower boundary. Hence, the stress-strain relations under arbitrary loadings can be approximated as described above, and by making an appropriate ruling of the boundary conditions on the basis of the latest stress-strain history.

Equation of Motion

The total stiffness matrix of this system, in which individual members have three degrees of freedom at each node, can be reduced to a combined stiffness matrix taking into consideration the two degrees of freedom, which permit the horizontal and vertical displacements at the three lumped masses.
Hence, the general equation of motion for this system subjected to both horizontal and vertical ground motions, as well as gravity load, at the time, t, takes the form:

$$[M]\{\ddot{u}_t\} + [C]\{\dot{u}_t\} + \{R_t\} + [K_t]\{\Delta u_t\} = -[M]\{\ddot{y}_0\} + \{v_0\} \tag{1}$$

where $[M]$: the diagonal matrix consisted of the masses,
$[C]$: the damping matrix,
$[K_t]$: the instantaneous stiffness matrix at the time t,
$\{R_t\}$: the restoring force vector accumulated from t=0 to t=t,
$\{v_0\}$: the load vector due to the gravity load,
$\{\ddot{u}_t\}$: the acceleration vector,
$\{\dot{u}_t\}$: the velocity vector,
$\{\Delta u_t\}$: the displacement vector at the time interval Δt , and
$\{\ddot{y}_0\}$: the horizontal and vertical ground accelerations.

At the initial state, the gravity load was gradually applied to the system. When this vertical load reached its designed level, the system was then subjected to both horizontal and vertical ground accelerations, as given in Eq.(1). A step-by-step numerical integration was performed adopting the Newmark β method (β =1/4).

Selection of Ground Acceleration Records

The acceleration records, JMA Kobe NS and UD, were selected and the data of their first fifteen seconds were used. The maximum accelerations measured from the original records were 818 gal for NS component and 332 gal for UD component, respectively. These acceleration records were used to analyze the dynamic behaviors of the frames without any modification of the records.

RESULT OF ANALYSIS

Stress-Strain Behaviors

The stress-strain outputs at the beam ends are typically shown as Figs. 7 and 8, when the frames are subjected to the acceleration record of the 1995 Hyogoken Nambu Earthquake. In the figures, the ordinates and the abscissas are normalized by dividing the stress and the strain outputs by the yield stress and the yield strain of the material. It can be seen that the flanges at the beam ends sustain severely great amount of plastic strain. Strain outputs show that there are two types of strain response patterns. One is single excursion in which the strain as much as the extent beyond the strain hardening region of the material. Another is well known cyclic inelastic excursions with a comparatively few number of reversals.

Aseismic design concept for the latter case, are popular in Japan and many seismic countries where the buildings are practically designed against earthquakes, which might be expected to occur far from the faults. However, in the former case, single excursion in the stress-strain relation are remarkably observed and then further research for aseismic design will be needed against earthquakes which occur very close to the faults.

The damage assessment for the Northridge earthquake, California in USA, occurred in just one year ago, has been investigated(Naeim, 1994). In the literature, it has been reported that the building structures were damaged without sufficient resistance due to a great amount of hysteretic energy of the components.

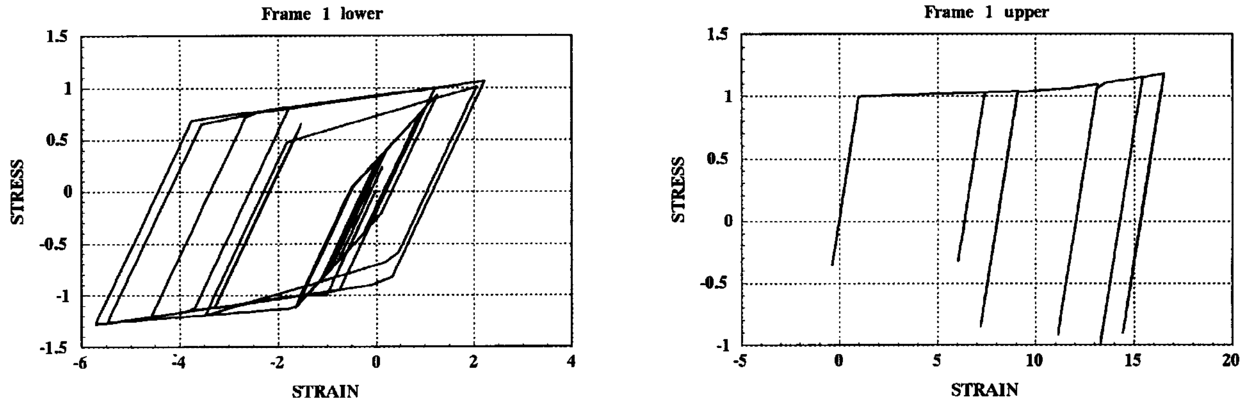

Fig. 7. Stress-strain relations of Frame 1

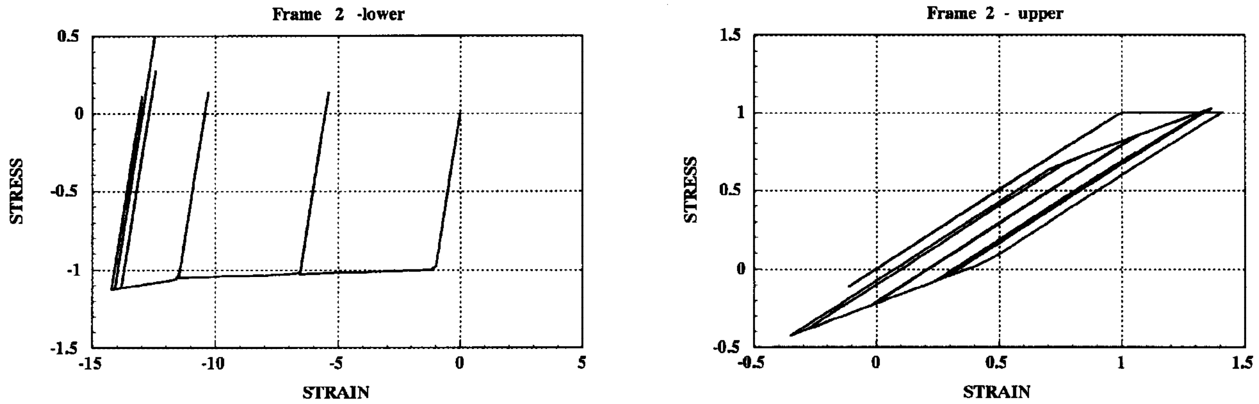

Fig. 8. Stress-strain relations of Frame 2

Strain rate measured from dynamic response

Strain rate of the beam flanges can be obtained by differentiating the strains shown in Figs. 7 and 8 by time. Typical strain rate resultants are shown in Figs. 9 and 10, for Frame 1 and 2, respectively. The strain rate at the critical sections reaches up to about 40%/sec,nevertheless the stress-strain relations exhibit monotonicaly or cyclicaly. Then it suggests that the failure at the welded joints is previous to the failure of the base metal and that single or few excursion failure mechanism has to be invesitgated against earthquakes occurring near fault regions.

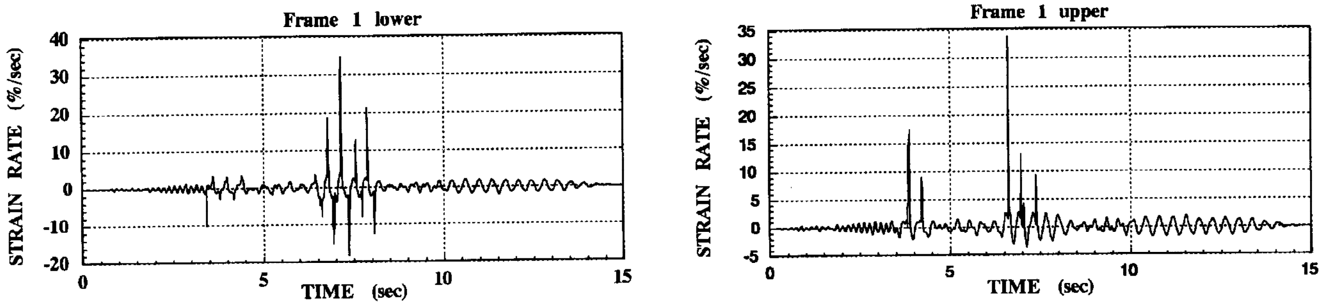

Fig. 9. Time histories of strain rate (Frame 1)

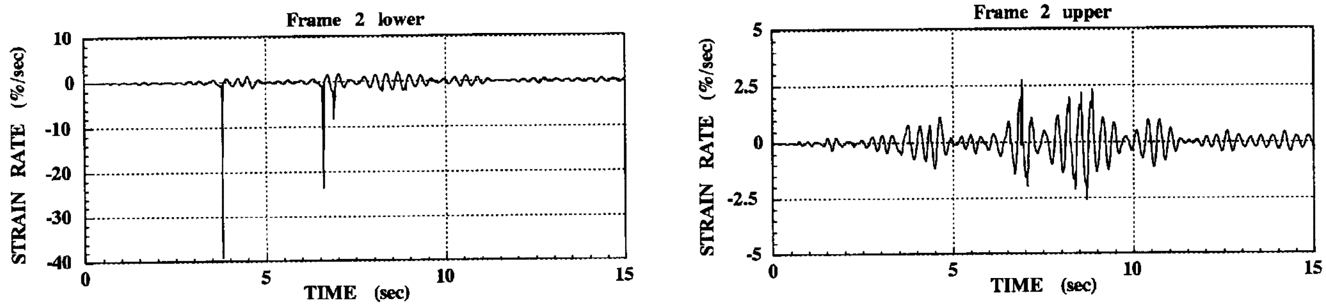

Fig.10. Time histories of strain rate (Frame 2)

CONCLUSIONS

In order to make clear the main source of the structural damage of the steel moment resisting frames,observed in the event of the 1995 Hyogoken Nambu Earthquake, the effect of strain rate on the strength of the welded beam-to-column connections and the effect of the simultaneous action of the horizontal and the vertical ground motion were examined through the experimental and analytical investigations. From both experimental and analytical results, the following conclusions have been drawn.

(1)The upward tendency of the yield ratio of the butt welded joint is significant in comparison with the tendency of the yield ratio of the base metal, with increasing the strain rate. Such phenomenon follows that the fracture can occur at the welded joints, when the frames are subjected to earthquake shocks.
(2)single or few excursion strain response with comparatively high strain rate is clearly observed at the beam flanges close to the beam-to-column connections, due to both horizontal and vertical motions of the earthquake. The premature failure without sufficient exhibition of energy dissipation occurs in the steel moment resisting frames, if the frames constructed right above or close to the fault are eventually subjected to earthquakes.

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