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THE EFFECT OF STRAIN RATE IN RESTORING FORCE CHARACTERISTICS OF STEEL BRACED STRUCTURES UNDER HIGH SPEED CYCLIC LOADINGS

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ABSTRACT

This paper deals with the results of loading tests using model structures with one-bay one-story for study of the effect of strain rate corresponding to the restoring force characteristics of steel braced structures. Comparing the results of static loading with those of dynamic loading having similar strain rate to the earthquake shocks, one of the most critical factors affecting the restoring force characteristics of the frames shall be the rise of yield points of brace in conformity with the increase of strain rate. On the other hand, the friction joint by high-strength bolts would not be so influential to the behavior of the whole frame, although the friction limits would be lowered as the load applying rates be increased.

KEYWORDS

dynamic loading test; strain rate; restoring force characteristics; moment resting frame; steel braced structures; steel structural joint; high-strength bolt;

INTRODUCTION

The effect of strain rate on the restoring force characteristics of steel frames is one of the most significant factors to assess the safety in the structures resisting against high speed loadings like earthquake shocks.

Suita *et al.*(1992) had reported on the results of the experiments on dynamic behavior of typical steel structural joints due to high speed cyclic reversed loadings. In that paper, it is concluded that the friction limits and the slippages of friction type bolts were remarkably affected by load applying rates under cyclically reversed loading conditions. The decrease of friction limits of high-strength bolted connections will be a significant problem to be taken into consideration on the seismic design of bolted joints, especially, in steel structures with short natural periods such as low-rise steel braced frames.

This paper reveals the results of experiments carried out for the purpose of studying the effect of strain rate on the restoring force characteristics of steel braced frames taking into account behaviors of bolted joints.

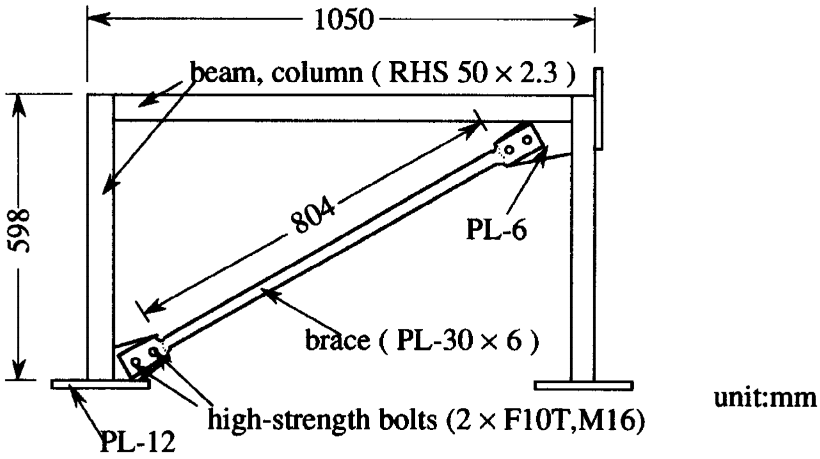

Fig. 1 Test specimen.

OVERVIEW OF TEST PROGRAM

Description of Test Specimen

The prepared test specimen is a small scale model structure on a scale of approximately one-fifth of its real dimension. As shown in Fig. 1, the style of structure is a moment resisting frame that is rigid one-bay one-story consisting of square hollow section columns and beam, and reinforced by a flat steel bar bracing arranged solely toward an inner diagonal direction on the plane of structure. This bracing with the slenderness ratio of 464 would be expected to offer resistance against the tensional forces. Both ends of the bracing shall be frictionally connected by high-strength bolts onto the gusset plates fixed on the frame.

Square hollow sections adopted for the columns and beam have a sectional size of 50 x 50 x 2.3 in millimeter and shall have been standardized to the JIS's structural steel STKR400 with 265N/mm^2 of nominal Y.P. and also 400N/mm^2 of nominal tensile strength, whereas the bracing has a sectional size of 30 x 6 in mm and with the same grade (SS400) of steel strength as the beam. Each end of bracing are frictionally jointed by two high-strength bolts of F10T and M16 respectively.

In order to prevent the bracing from premature yielding at the joints, the width of brace is enlarged to 54 mm around its bolted connections. Consequently the lateral strength of the test specimen is properly designed to increase in due order of the yield strength of the brace axis, the yield strength of the columns and beam, and the slip proof strength of the bolted connections.

Furthermore, for the comparative study of functional effect of the bracing, an another moment resisting frame which is made from only columns and beam without bracing is also prepared.

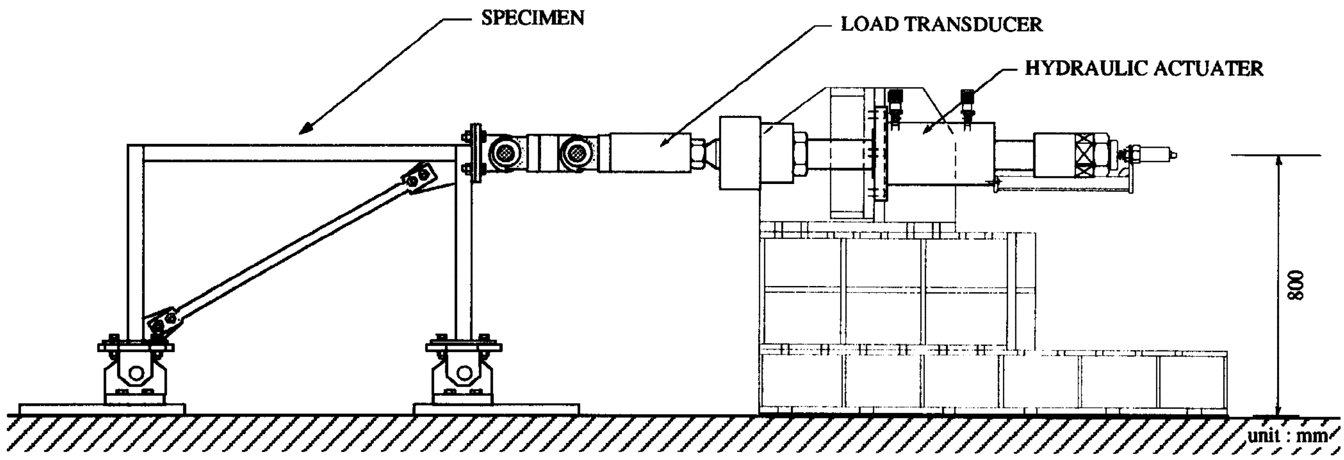

Fig.2 Loading apparatus

Testing Procedure

Fig. 2 denotes the test specimen situated on the loading apparatus. Its bases of columns are pin supported to the test bed and guarded by the jigs for prevention of the outward deformation. The lateral force is applied onto the test frame by means of the servo-mechanical hydraulic actuator through a pin jig installed at the beam-to-column joint on one side.

In the experiment, measured ones are the applied load by means of the load transducer fixed at the end of hydraulic actuator, the transverse displacement at the loaded point and also the axial displacement of the brace axis and its both ends connections by means of the laser displacement transducer, and then the local strains on the columns, beam and bracing through the wire strain gages.

Two kinds of load application which are the monotonic loading and the cyclic reversed one are adopted, both of them are started toward the direction where the bracing suffers the tensional forces at the initial loading. The strain rate during applying loads is controlled by the speed of movement of the cylinder of hydraulic actuator. The experiment is performed with two kinds of loading speed that are the dynamic load of 35 mm/sec and the static one of 0.053mm/sec. The amplitude of displacement of the cyclic reversed loading is 50 mm (1:13.5 of story deformation angle) and the repeated time is 5. The dynamic loads are repeatedly applied by the fixed displacement amplitude, whereas the static loads is gradually increased by 10 mm on each amplitude.

It has been reported that the strain rate of low-rise braced frames suffering earthquake shocks would be evaluated as follows; 0.1 sec^{-1} on column portion, 0.15 sec^{-1} on brace axis, and approximately 3 to 3.5 sec^{-1} at around connection bolt holes. (Aoki *et al.*, 1982, Fujimoto *et al.*, 1988) As a results of the experiment, the strain rate that is nearly same as the estimate aforesaid has been acquired as described hereinafter.

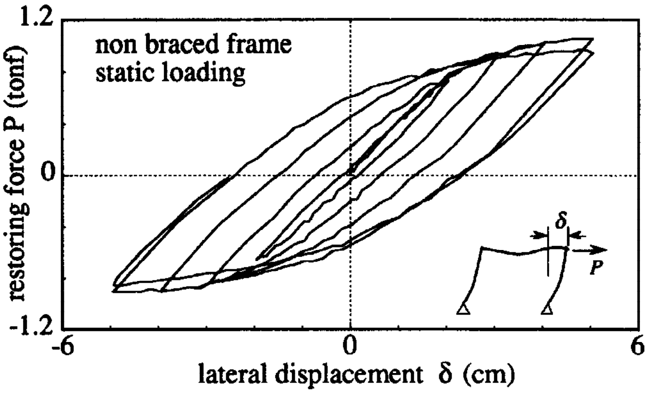

Fig.3 Hysteretic behavior of the specimen without bracing under static loading

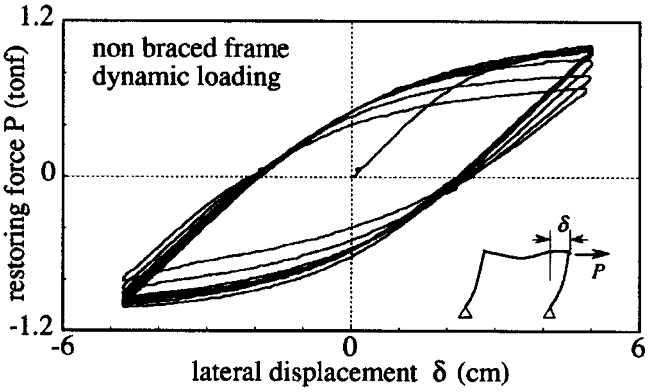

Fig.4 Hysteretic behavior of the specimen without bracing under dynamic loading

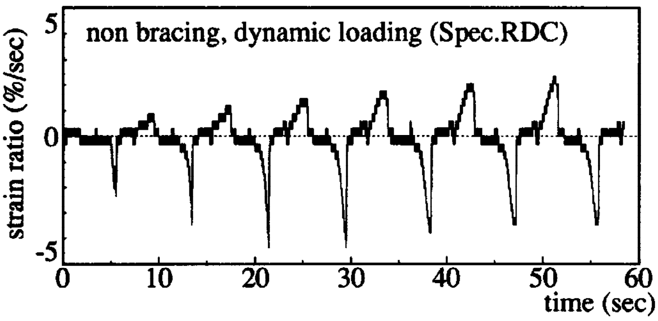

Fig.5 Strain rate history of the column member

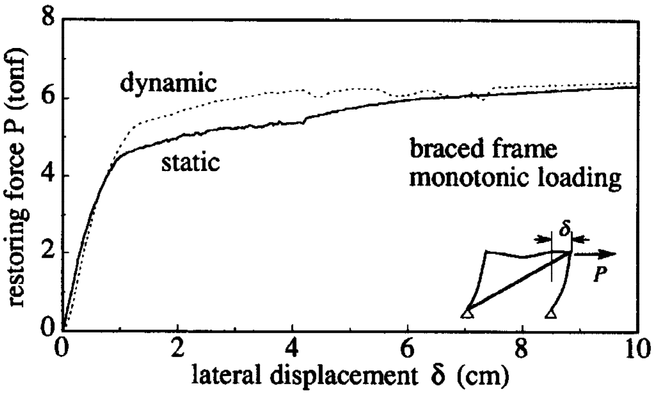

Fig.6 Hysteretic behavior of the specimen with bracing under monotonic loading

TEST RESULTS

Restoring Force Characteristics of Moment Resisting Frame without Bracing

The restoring force characteristics of moment resisting frame without bracing are indicated in Fig. 3 (static load application) and Fig. 4 (dynamic one). There is almost no difference between both restoring force characteristics when only strain rates differ each other on the same test specimen. Most of the local strain rates, obtained through the wire strain gages, due to bending deformation at the edge portions of the column and beam during the dynamic loading are around 0.01 sec^{1} although some of them reach 0.05 sec^{1} in maximum as shown in Fig. 5. The strain rates are generally small and would not be remarkably influential to the restoring force characteristics of the whole frame.

Restoring Force Characteristics of Moment Resisting Frame with Bracing (Monotonic Loading)

The restoring force characteristics of moment resisting frame with bracing under the monotonic loading are as shown in Fig. 6. The solid lines and the dotted ones denote the results of the static loading and the dynamic one respectively. In case of the dynamic loading, the remarkable increase of the restoring forces is found. The

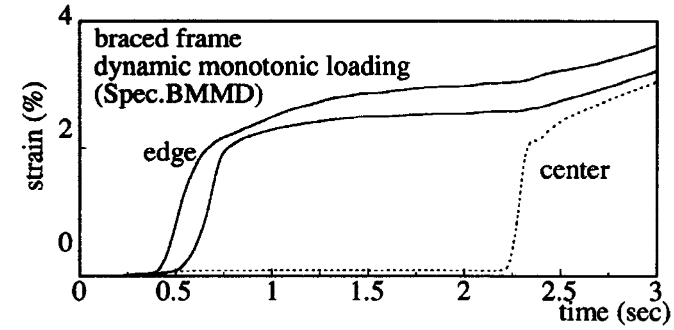

Fig.7 Strain hostory of the bracing

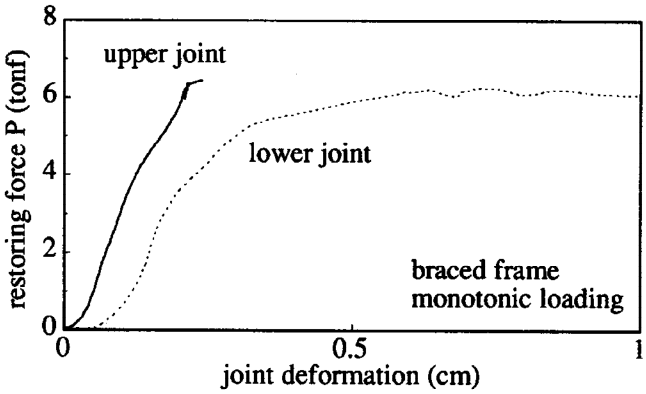

Fig.8 Relative deformation between the brace ends and the gusset plates

yield strength of the frame, that has been obtained through the experiment, is 4.40 tonf on the static loading and also 5.20 tonf on the dynamic loading. About 18% of the strength is supposed to be increased.

Following are the reasons why the yield strength is remarkably increased when the frame is braced; The first is that the lateral strength of the frame depends substantially on the tensile strength of the bracing. The second is that the strain rates of the bracing that mainly bears the axial forces are much larger than those of the column and beam due to their bending deflection.

Fig. 7 indicates the change of the local strains obtained through the wire strain gages during a few seconds of the dynamic loading and caused by the deformation toward the longitudinal direction of the brace axis. It is found that remarkable enlargement of strains at the edge portion around 0.5 sec after starting load application and the next at the center portion around 2.2 sec after. The strain rates are from 0.13 to 0.25sec^{-1} when these strains are rapidly increased. Accordingly the yielding of brace occurs locally at the edge portion close to the bolt connections, the strain rate falls when the strains reach around 2% of the beginning point of strain hardening, and the yielding of the neighboring portions follows. At last the bracing is wholly yielded and high strain rates are kept in the yield developing areas of the bracing during its yielding.

The restoring force characteristics under the dynamic loading in Fig. 6 show fluctuations of the restoring forces in the range of 4.5 - 7.5 cm of lateral displacement. These are because of the slippages of friction joints at the edges of the bracing. Fig. 8 indicates the relative deformation between the brace ends and the gusset plates at the both edge jointings. The upper end joint of the bracing hardly has slippage whereas the lower one has evident deformation due to its slippage.

There are instances where the slip strength at friction joint by means of high-strength bolts would fall in compliance with the increase of loading speed (Suita *et al.*,1992). In this experiment the occurrence of apparent slippage has been observed only under the dynamic loading similarly.

In Fig. 8 there is deformation due to a large slippage over 1 cm. However, this is because of the falling off of the displacement transducer by slipping vibration of the friction joint, and its actual deformation shall be 2 mm

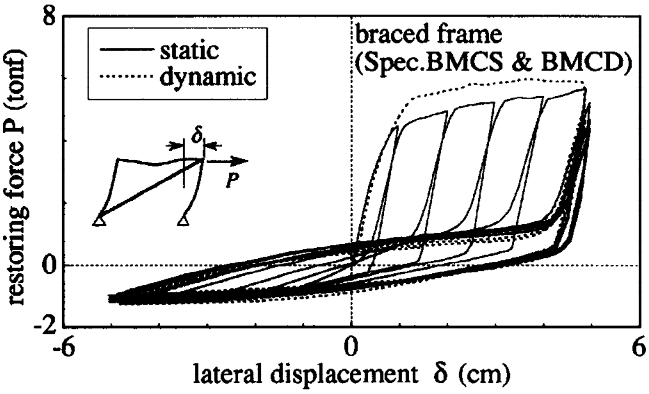

Fig.9 Hysteretic behavior of the specimen with bracing under cyclic reversed loading

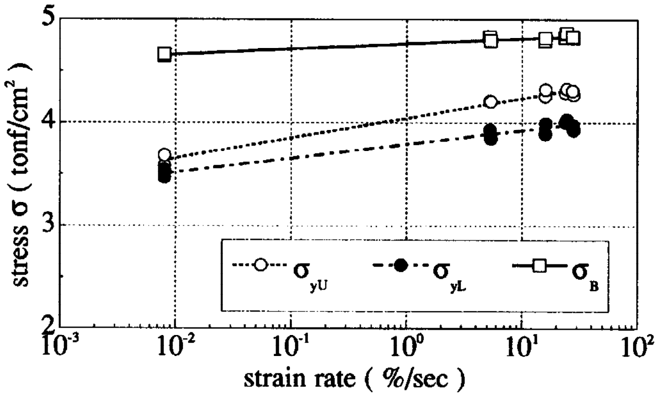

Fig.10 Yield strength versus strain rate relationship of brace member steel

that is equivalent to the clearance of bolt hole. Therefore this deformation does not affect the restoring force characteristics of the whole frame.

Restoring Force Characteristics of Moment Resisting Frame with Bracing (Cyclic Reversed Loading)

The restoring force characteristics of moment resisting frame with bracing under the cyclic reversed loading are as shown in Fig. 9. The solid lines and the dotted ones denote the results of the static loading and the dynamic one respectively.

Under such the positive direction of loading that the bracing suffers tension, the apparent increase of the restoring force are observed in accordance with the rise of loading rate in the same manner as the monotonic loading aforesaid. The uprise of the yield strength of the frame is, alike the case of monotonic loading, in compliance with the ascent of the yield point of the brace in the same extent as the monotonic loading.

On the contrary, under such the negative direction of loading that the bracing suffers buckling of compression, there is little difference of the restoring force depending on the loading rate. The reason is that the slenderness ratio is large, and then the buckling strength depends on the Young's modulus and is determined by the Euler's load that is independent on the yield point. Namely, that is supposed to be why the Young's modulus is hardly affected by the strain rate whereas the yield point of steel materials is obviously affected by it.

Moreover, since all of the deformations at the bolted connection under the cyclic reversed loading are within the clearance of the bolt holes, no slippage of bolts seems to have occurred.

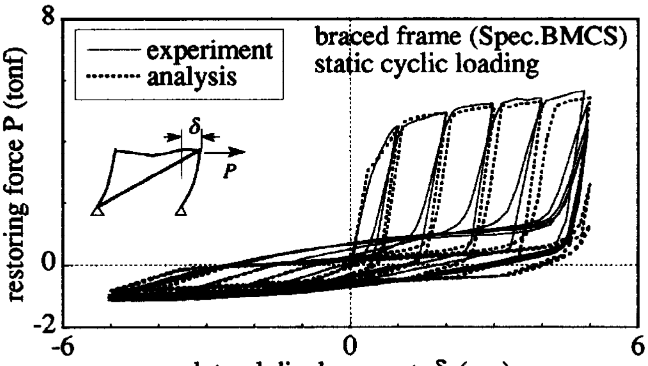

Fig.11 Comparison of hysteretic behaviors under static loading

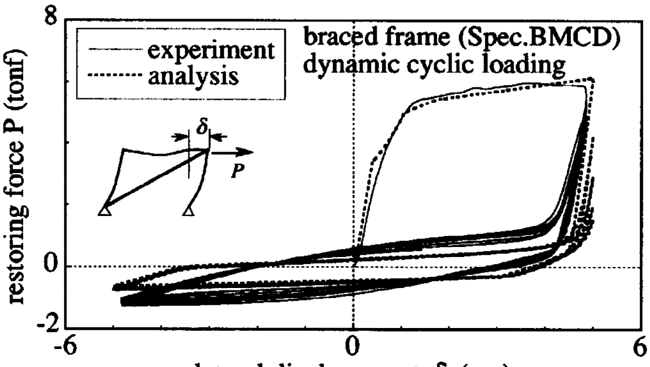

Fig.12 Comparison of hysteretic behaviors under dynamic loading

NUMERICAL ANALYSIS

From the results of this experiment, it would be presumed what most affect the restoring force characteristics of the frames in which tensional bracing bears the lateral forces contributively shall be the effect of strain rate against the yield point of the bracing. This presumption was verified by means of the numerical analysis in consideration of the effect of strain rate against the yield point of steel materials hereinafter.

Fig. 10 denotes the effect of strain rate against the yield strength and the fracture strength, that is obtained from the results of coupon test of the same kind of steel material as the brace in the test specimen (Suita*et al.*, 1994). Following formula is for the relation between the strain rate and the value acquired by making the lower yield point σ_{yL} (tonf/cm^2) shown as the black painted circles there non-dimensioned by the lower yield point σ_{yL0} (tonf/cm^2) under the static loading ($\dot{\varepsilon} = 8 \times 10^{-3}$ %/sec);

$$\sigma_{yL}/\sigma_{yL0} = 1.08 + 0.038 \log_{10}|\dot{\varepsilon}| \qquad (1)$$

When $\dot{\varepsilon}$ = 19.46 %/sec: the average of strain rate of the bracing from the experimental results and also σ_{yL0} = 3.128 tonf/cm^2: the lower yield point under the static loading of coupon test are substituted into (1), the lower yield point under the dynamic loading will be σ_{yL} = 3.532 tonf/cm^2.

Furthermore, when $\dot{\varepsilon}$ = 3.80 %/sec: the strain rate due to bending of the columns and beam and then σ_{yL0} = 3.700 tonf/cm^2: the lower yield point under the static loading are substituted into (1), the lower yield point under the dynamic loading will be σ_{yL} = 4.077 tonf/cm^2.

The results of numerical analysis by the stiffness matrix method with the yield points described above under both of the static loading and the dynamic one are as shown in Fig. 11 (static loading) and Fig. 12 (dynamic loading). The solid lines and the dotted ones denote the results from the experiment and those of the numerical analysis respectively. In both cases the results of numerical analysis are almost equivalent to those of the experiment, the restoring force characteristics of the test frame is well simulated with sufficient accuracy. Thus the differences of restoring force characteristics corresponding to the loading rate would be evaluated by taking account of the effect of strain rate against the yield point.

CONCLUSIONS

The effect of strain rate on the restoring force characteristics against the lateral force in the steel frame consisting of tensional brace, columns and beam has experimentally assessed, and proved as follows;

The restoring force of the whole frame will be increased in conformity to the ascent of the loading rate. Among brace, column/beam members, and bolted joints, the brace bearing tension will most affect the behavior of the whole frame and its prime factor is the uprise of the yield point in compliance with the strain rate.

It will be possible to analytically obtain the behavior of frame under the dynamic loading without fracture and within the nonlinear region of materials by acquiring the principal strain rates in the plastic region and then evaluating the yield point under the results of coupon test.

The slippages on the frictionally bolted joints at the brace ends would occur often with the increase of loading rate. However, within the scope of this experiment, it has hardly affected the behavior of the whole frame.

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