

Zeitschrift: IABSE congress report = Rapport du congrès AIPC = IVBH
Kongressbericht

Band: 9 (1972)

Artikel: Bracing system composed of high-strength steel bars as adopted in
aseismic design of a high-rise building

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DOI: <https://doi.org/10.5169/seals-9567>

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Bracing System Composed of High-Strength Steel Bars as Adopted in Aseismic Design of a High-Rise Building

Système de raidissement composé de barres de haute résistance adoptées pour un immeuble de plusieurs étages soumis aux séismes

Aussteifungssystem aus Stahlstäben hoher Festigkeit, wie es beim Entwurf erdbebengeschützter hoher Gebäude angewendet wird

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1. Introduction

The bracing system as a structural element can increase the rigidity of a building and enables it to resist effectively against overturning moment more economically than if the genuine rigid frame is used. The conventional bracing system usually insures satisfactory results as far as wind resistance is concerned. It, however, often turns out to be unsuitable for the aseismic design of a building because the rigidity usually becomes too high and inadequately distributed if such a bracing system is used. Consequently, it ends up in a structure subject to large shear forces and liable to unsatisfactory earthquake responses. This means that the merits of the bracing system needs to be evaluated quite differently depending on whether the design must be wind-resistant only or aseismic as well as wind-resistant.

This report deals with a case wherein the bracing system composed of high strength steel bars was assessed through the tests and the computations on braced frame units in an attempt to find a structural system which could provide a sufficient strength without adversely increasing rigidity. The bracing system as described above was adopted actually for the 26-storeyed KTC Building (the Kobe Commerce, Industry and Trade Center Building in Kobe, Japan).

2. Bracing System with High-Strength Steel Bars

For the section design of the members of high-rise building subject to lateral forces (wind load and seismic excitation), it is a general practice to determine the sections on the basis of elastic theory for the loads that occur frequently, and on the basis of elasto-plastic theory for the loads that occur less frequently.

Because the bracing system increases the rigidity of a building particularly in lower storeys and the braces themselves have large share in shear rigidity, the lateral force is concentrated in the brace system, thereby causing large stress in bracing. Thus, if mild steel with ordinary strength is used for such braces, the existing stress in the braces is likely to reach the yield point readily by the external force which may occur rather frequently. Consequently, the structure might retain a residual deflection even after external force is removed. This phenomenon is not desirable because it virtually lowers

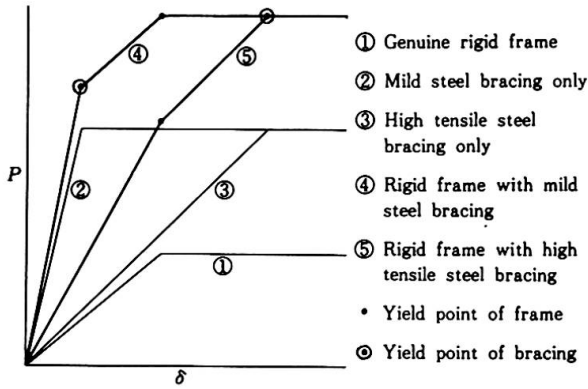


Fig. 1 Idealized expression of bracing system

the initial rigidity of building. Moreover, large axial forces will be concentrated on the braced end columns under lateral load. The foregoing disadvantage can be greatly eliminated if high strength steel bars are used for those braces because the use of such bars gives the structure a wider elastic range without pronounced increase of the rigidity. Fig. 1 represents idealized expression of the structural phenomena described above. Thus, such a bracing system insures a structural system with adequate rigidity distribution which results in more satisfactory earthquake responses.

The KTC Building is featured by a structural system as shown in Figs. 2 and 3. Its main framework is composed of a core made up of frames braced with high strength steel bars and of perimeter frames which are in the form of a genuine rigid frame. The sharing and distribution of shear forces among these and other frames during an earthquake are indicated in Fig. 4. A structure well balanced under both wind load and seismic excitation was made possible by a brace system consisting of high strength steel bars (27 - 32 mm in diam., upset and threaded at both ends).

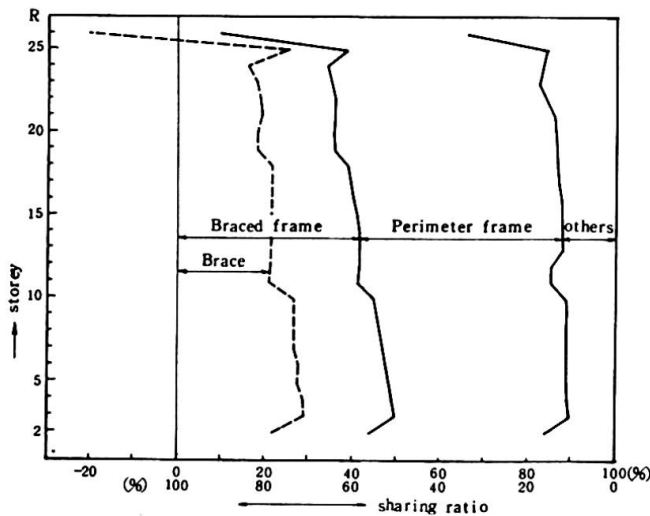


Fig. 4 Seismic load sharing

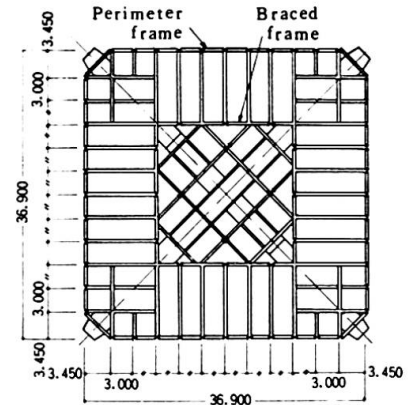


Fig. 2 Beam plan

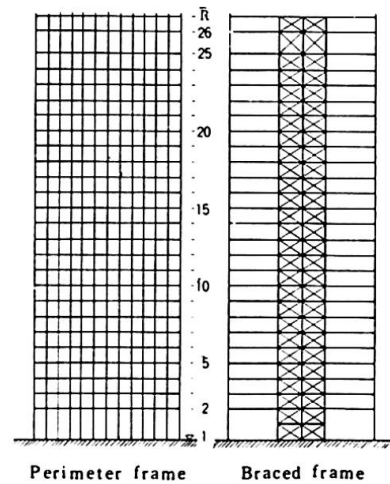


Fig. 3 Structural system

3. Experiments

3.1 Test Specimens

Two types of specimens were prepared. F-2 was a 2-storeyed single-bay braced frame and F-1 was a non-braced rigid frame for comparison, both reduced to 1/2 of the actual structure in scale. The columns and beams of the specimens were designed to have the section modulus (Z) approximately equal to 1/8 of that of the actual members except for the intermediate beam which, in consideration of the influence of adjoining members, was designed to have a Z-value approximately equal to 1/4 of the actual

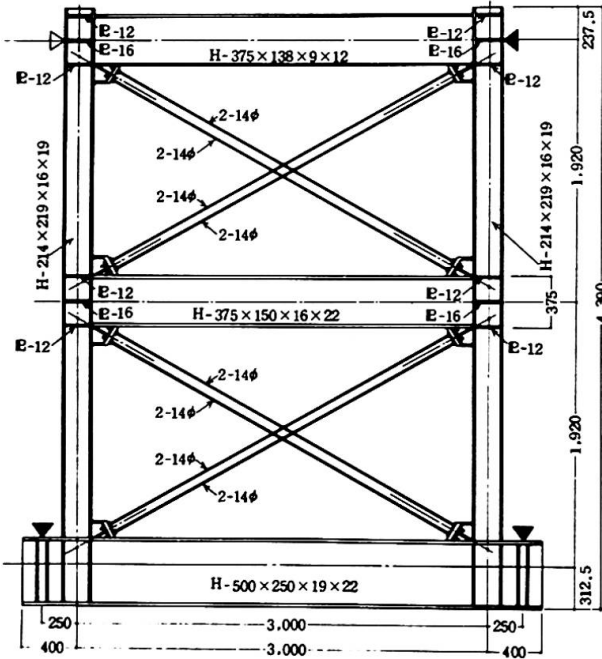


Fig. 5 Test specimen F-2

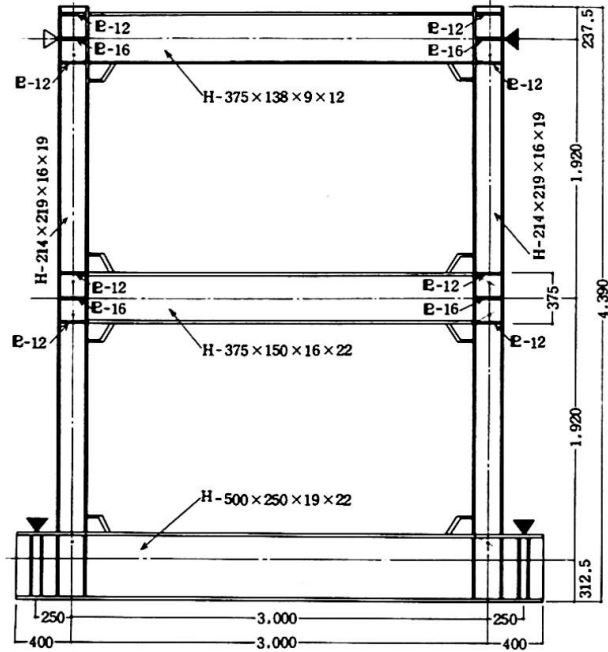


Fig. 6 Test specimen F-1

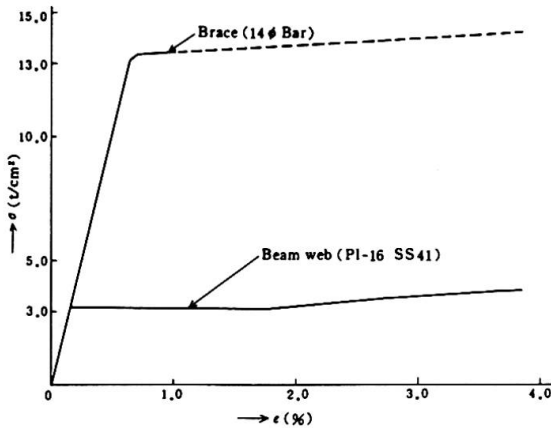


Fig. 7 $\sigma - \epsilon$ relationship

Table 1 Materials

PL-thickness	Member	Quality	Yield point (t/cm ²)	Tensile strength (t/cm ²)	Elongation (%)
PL- 9	Beam web	SS41	3.56	4.70	31.3
PL- 12	Beam flange	SS41	2.78	4.28	31.3
PL- 16	Beam web	SS41	3.17	4.32	31.0
PL- 22	Beam flange	SS41	2.84	4.65	31.0
PL- 16	Column web	SM50A	3.74	5.39	29.3
PL- 19	Column flange	SM50A	3.88	5.37	31.0
14 φ	Brace	Gr. 4	12.8	13.6	7.5

member. The sectional area of bracing bars was about 1/4 of the actual area. The qualities and mechanical properties of steels used are shown in Fig.7 and Table 1.

3.2 Results of the Experiments

The results of the experiments are shown in Figs. 8 through 11 by the solid lines. Figs. 8 and 9 show the load-deflection relationships at the top of columns in upper and lower storeys of F-2 and F-1 specimens respectively. Figs. 10 and 11 show the load-curvature relationships calculated from the strains measured with wire strain gauges at the top and bottom of the cross section (marked by o) of column and beams of specimens F-2 and F-1 respectively. The photos show the specimen F-2 in final state after the test.

3.3 Analyses

The stress and deformation analyses of frames were made by the "plastic hinge method". The relationship between bending moment (M) and curvature (ϕ) in each member was assumed to be purely elasto-plastic as shown in Fig. 12. Then, the elastic analyses were made of the deformation which took place between the

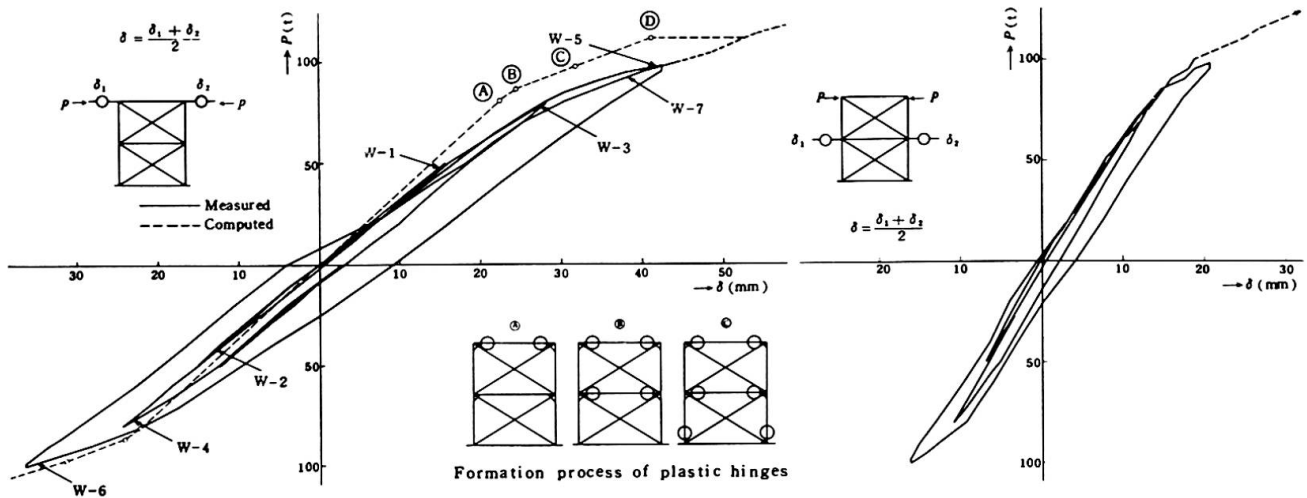


Fig. 8 Load-deflection relationships F-2

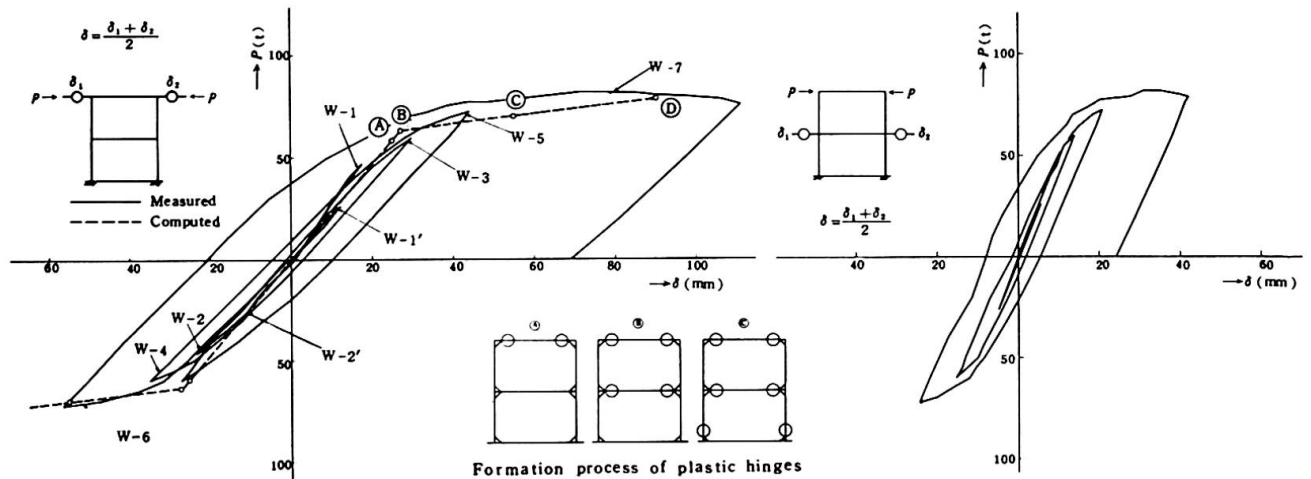
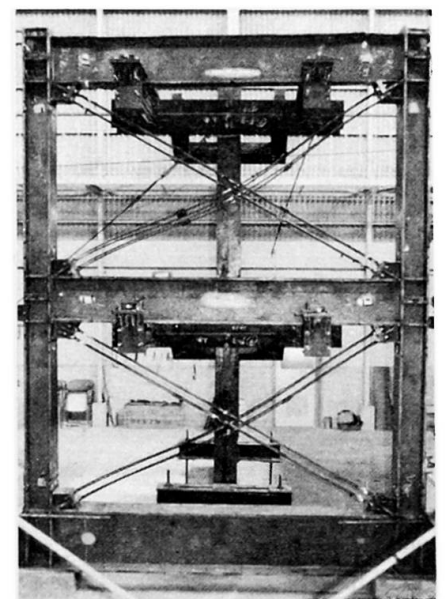


Fig. 9 Load-deflection relationships F-1

stage where a certain plastic hinge was formed and the next stage where another plastic hinge was formed. The results of analyses are shown by a dotted line in Figs. 8 and 9.

The assumptions used in analyses were as follows:

- (1) The sections of end portions of columns and beams were calculated inclusive of the gusset portions.
- (2) Bending, shearing and axial deformation was considered for the calculation of columns and beams.
- (3) Shearing deformation in the joint panels was considered.
- (4) Braces were assumed as pinned at both ends, taking the eccentricity from the panel center into account.
- (5) The eccentricity was dealt with by extending rigid arms from the column-beam intersections in line diagram.



Final state of specimen F-2 after the test

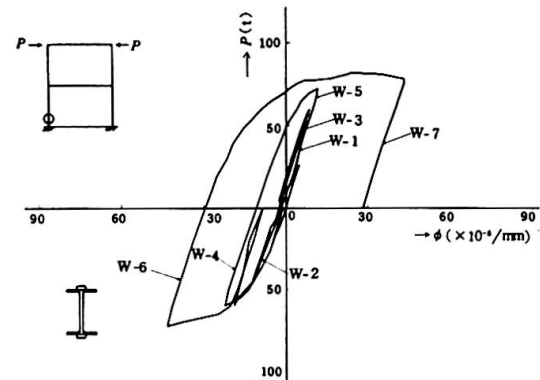
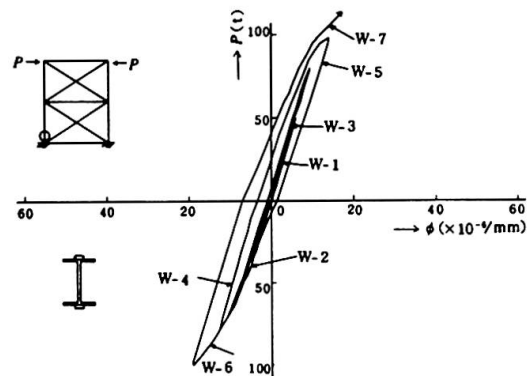
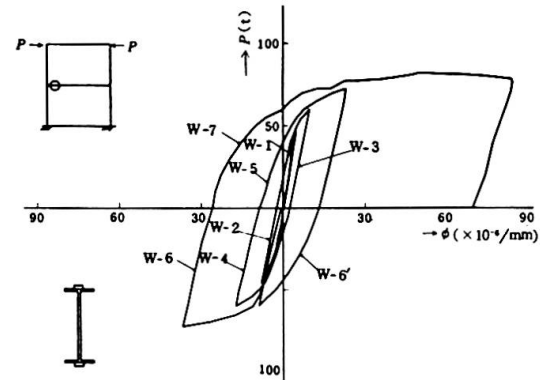
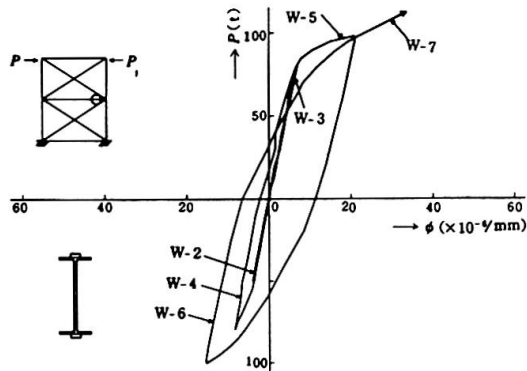
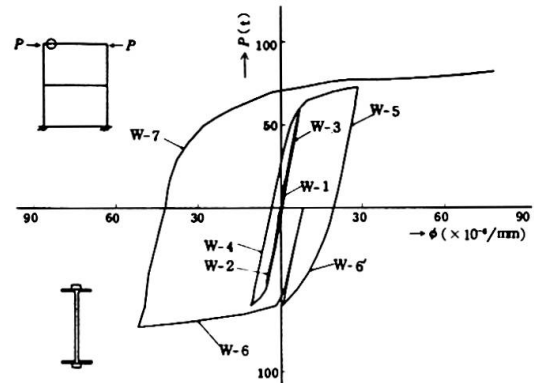
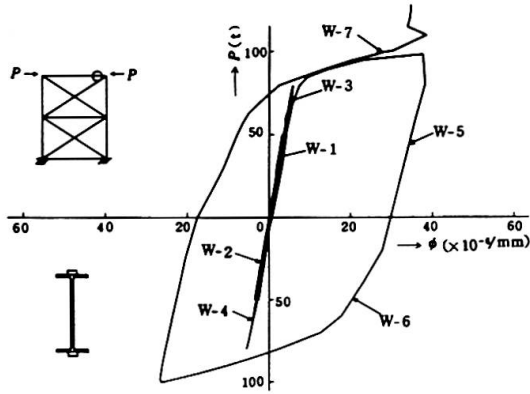


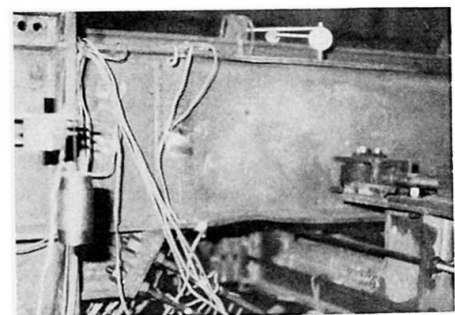
Fig 10 Load - curvature relationships F - 2

Fig.11 Load - curvature relationships F - 1

(6) Axial deformation of the braces was considered.

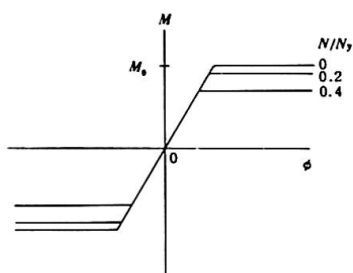
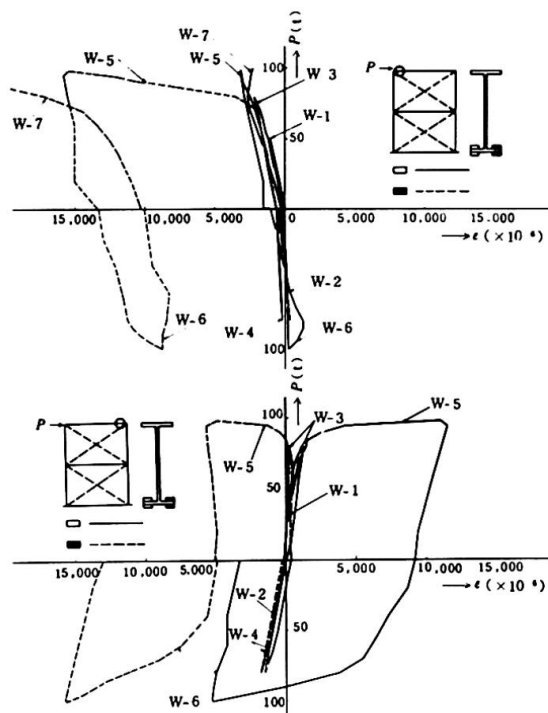
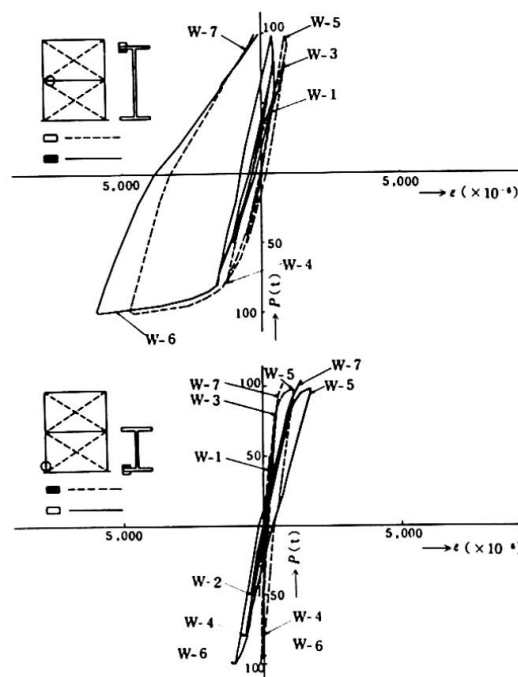
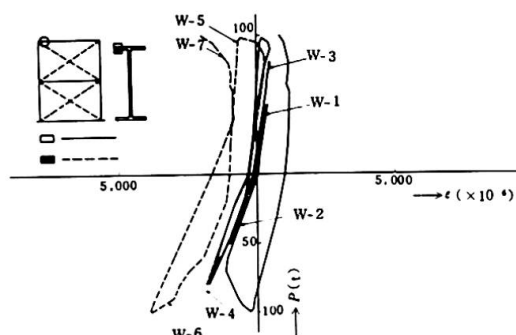
3.4 Discussions

The results of analyses and experiments are in reasonably good agreement with regard to the rigidity, strength and plastic-hinge formation process both in the elastic and the elasto-plastic ranges. As for the load-deformation relationship of the frames, in spite of the occurrence of the local and lateral bucklings at the final stage (see Figs. 13 and 14), the frames exhibited stabilized behaviors showing increased strength as the deformation progressed until extremely large deformation took place. The reduction of the initial rigidity due to cyclic loading was not noticeable. The high strength steel bar braces were still in elastic range even after a large deformation had occurred in the rigid frame, and the braces as tension bars coped well with the deformation of rigid frame.



Final state of specimen F-2 after the test

Final state of specimen F-2 after the test

Fig. 12 Assumed $M - \phi$ relationshipFig. 14 Load-strain relationships F-2
(Lateral buckling)Fig. 13 Load-strain relationships F-2
(Local buckling)

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Summary

In aseismic design of high-rise buildings, high-strength steel bar bracing contributes to the desired selection of the values of rigidity and their distribution in a building and thus insures satisfactory earthquake responses.

The structural behaviours of such bracing system were studied by the cyclic lateral load tests on 1/2 scale models. From the test results, it was proved that high strength steel bar provides a satisfactory and adequate material for the bracing system of high-rise buildings which must be earthquake-resistant.