Theme III: Experimental studies concerning steel structures, their elements and their connections

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Experimental Studies concerning Steel Structures, their Elements and their Connections

Etudes expérimentales concernant les structures en acier, leurs éléments et assemblages

Experimentelle Untersuchungen an Stahlbauten, ihren Elementen und Verbindungen

MORIHISA FUJIMOTO
Professor
Tokyo Institute of Technology

TAKEO NAKA
Prof., Emeritus
Tokyo University

Tokyo, Japan

1. INTRODUCTION

The objectives of structural design and researches are to reappear the behaviors of a completed structure that may be subjected to dead loads, live loads, wind loads and seismic loads and, based on the above results, are to design and construct safe structures satisfying economical requirements. Although innumerable researches have been carried out in each country and enormous energy has been devoted to these objectives, all of the problems have not been necessarily solved to date, mainly because the natural phenomena such as earthquakes and natural winds have to be dealt with and eventually they include many indefinite factors. Recent researches, however, have been making a remarkable progress. Especially, well-developed technics of numerical analysis utilizing digital computers give us precise informations about deformations and stresses of detailed structures at the design stage*1, and particularly they brought forth dynamical elasto-plastic design method which made possible to construct high-rise buildings in the cities in Circum-Pacific seismic zone*2.

The behaviors of structures at a very disastrous earthquake are dynamical random ones; dynamical random elasto-plastic vibrations due to random earthquake motions. Therefore, the action of dynamical random repeated forces should be taken into consideration in order to obtain data such as low-stressed high-cycle fatigue or high-stressed low-cycle fatigue necessary in estimating the behaviors of structures. At present, however, quasistatic actions of well-defined repeated force are dealt with in most cases.*3. In this paper, are reported the behaviors of steel structures, their elements and their connections subjected to such repeated forces.

For the structures which may be attacked by strong winds e.g., typhoon, cyclone and hurricane etc., aeroelastic phenomena such as buffeting, aeolian vibration, galloping and flutter should be taken into consideration. In these cases, the stresses will remain mostly in elastic range, and problems such as low-stress high-cycle fatigue or comfatability of occupants should be considered. Yet, the above problems are beyond the scope of this report.

From the above viewpoint, the behaviors and mechanical characteristics of;

(1) Materials
(2) Local buckling of plate elements

*1 For instance, see Ref. 1).

*2 See Ref. 2), 58), for instance.

*3 In Ref. 3), related to earthquake loading, dynamic test by force generator is compared with simulations in quasistatic manner and it is reported that both results show a good agreement.

(3) Compression members
(4) Beams and columns
(5) Mechanical fasteners and welding
(6) Connections
(7) Unbraced frames
(8) Braced frames

under well-defined repeated force are considered in this report.

2. MATERIALS

a. Lowering of proportional limit

Fig. 1 shows stress-strain diagram under repeated tension and compression, of structural steel of which tensile strength is 50 kg/mm². In the virginal loading, the upper yield point, the lower yield point, the plateau and strain hardening appear clearly. On the other hand, in subsequent loadings, these properties disappear and the proportional limit markedly decreases due to well-known Bauschinger effect.[4),5)]. At present on the mechanical treatment of steel structures, steels are usually treated that they posses such prominent properties as yield point, plateau and strain hardening. As far as the repeated loading beyond elastic range is concerned, however, the stress-strain diagram with no plateau should be applied instead. There should be payed more attentions to the possibilities that the lowering of proportional limit in each loading cycle may cause directly structural failure (for instance, buckling), increase of deformations and reduction of rigidity, of structural members, connections and cross section of members.

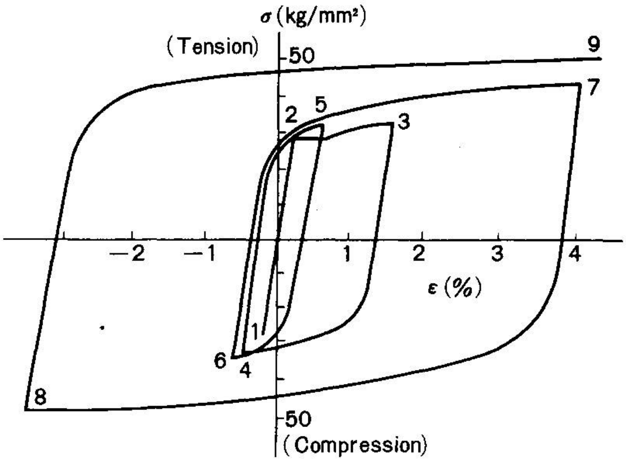

Fig. 1 Stress-Strain Relationship of a Structural Steel SM50 under Repeated Tension-Compression.

b. low-cycle fatigue

Among the theories of failure of materials, well-know von Mises' criterion of yielding;

$$(\sigma_x-\sigma_y)^2 + (\sigma_y-\sigma_z)^2 + (\sigma_z-\sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2) = 2\sigma_Y^2$$

in which σ_Y denotes yielding stress in simple tension, are commonly used for steels. Here, from the viewpoint of plastic hysteresis, it becomes necessary to establish condition of failure of steel in the range of large strains beyond yielding. In other words, this is low-cycle fatigue, which has been remarkably concerned recently. Considering possibility of occurance of brittle fracture due to applied-tension to the direction perpendicular to that of rolling (Fig. 2)[7)] and considering the influence of plastic strain on the notch toughness of steels*1, it becomes necessary without delay to

*1 For instance, see Ref. 8). It is reported that the transition temperature by impact test rises as much as 20° in case of 3% of pre-strain.

establish condition of failure of steels under various types of repeated loading.*1.

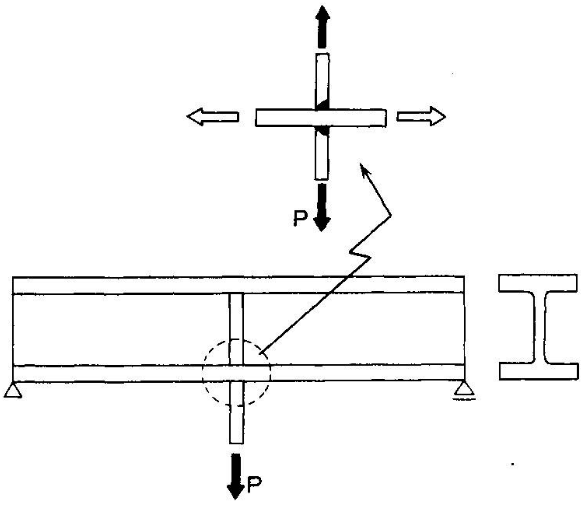

Fig. 2

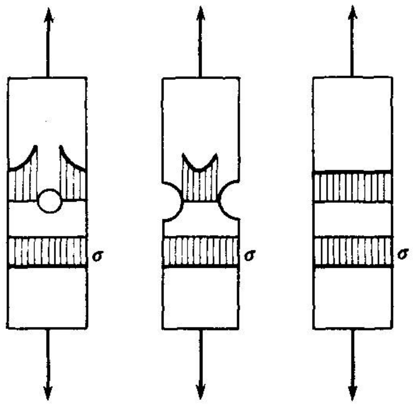

Fig. 3

c) Elongation capacity

When tension is applied to the steel members in which abrupt change of sectional area exists as shown in Fig. 3, yielding concentrates on the abruptly changed section and total elongation considerably decrease.[9)]. This tendency is notable particularly in case of high-strength steels with high yielding-strength ratio, which has been used widely now. Such structural discontinuities are unavoidable in frames and members and thereby it is necessary to understand their properties including the influences of repeated force, taking account of relationship with section b) above.

3. LOCAL BUCKLING OF PLATE ELEMENTS

As for the buckling of the plate elements such as flanges and webs, many researches have been carried out in case of simply compressed loading, as one of the fundamental problems in relation to the rotational capacity of yield hinges in plastic design.*2. For instance, in case of A-7 (σ_Y = 33KSI, 23 Kg/mm^2), the width-thickness ratio requirements of H-shaped section as illustrated in Fig. 4(a) are;

i) under the condition not to allow for local buckling of flanges to occur until plastic strain reaches the end of the plateau i.e., the starting point of strain hardening,

$$b/t_f \leqq 17$$

ii) under the condition not to allow for local buckling of webs to occur until plastic strain reaches $4 \cdot \epsilon_Y$ ($\epsilon_Y = \sigma_Y/E$),

$$43 \leqq \frac{d}{t_w} \leqq 70 - 100\frac{P}{P_Y}$$

in which, $P_Y = \sigma_Y \cdot A$, where A denotes sectional area of H-shaped section.

The local buckling behavior of plate elements subjected to plastic hysteresis due to repeated loads appears differently compared with that in case of monotonic loading due to the lowering of proportional limit in each loading cycle, as stated in section 2.a. This problem is dealt with incidentally in the experiments of members and connections under repeated loading. From the above viewpoint, in Ref. 14), 15), 16), 17) and 57), the local buckling are dealt with in cases of beams and

*1 This kind of problems are vigorously investivated in ship-building engineering. For instance, see Ref. 29).

*2 For instance, see Ref. 10), 11), 12), 13).

columns, particularly as to beam-to-column connections, and also in cases of cantilevered beams and simply supported beams. In those investigations are reported interesting results including plastic hysteresis in post local buckling. The local buckling of plate elements are accentuated by the action of repeated force, and large distortion in panel zone induces local buckling of flanges in beam-to-column connections as illustrated in Fig. 4(b). Nevertheless, it should be noted that local buckling of flanges does not lead to a significant drop in strength and rigidity.[57]

Hereafter, it is expected that series of researches will be undertaken concerning on the local buckling of plate elements with different width-thickness ratios and concerning on post buckling behaviors under repeated loading.

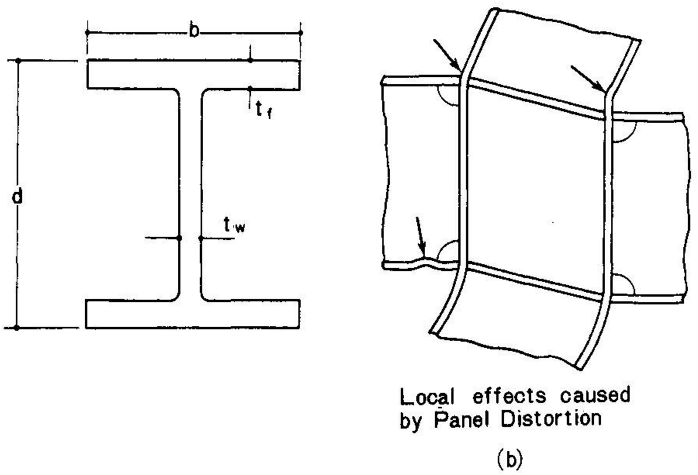

Fig. 4

4. COMPRESSION MEMBERS

There are few experiments for compression members subjected to plastic hysteresis by repeated loading. Fig. 5 shows P-δ curve obtained from experiment, in which a bar of rectangular cross section with slenderness ratio of 120 is subjected through pinned ends to repeated tension and compression, gradually increasing strain amplitude in each loading cycle.[23] It should be noted that compression member loses its resistance considerably once it buckles. Fig. 6 shows theoretical P-δ curve of a bar, in which yield hinge is assumed in mid-section in post buckling and furthermore plastic deformation of member is neglected. In this analysis, because it is assumed that a bar recover a perfectly straight form at E, the buckling load in the second compressive loading cycle is equal to the first buckling load, A.

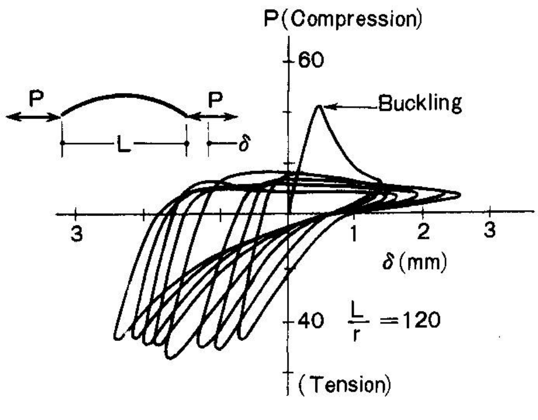

Fig. 5 Hysteresis Loops of a Bar under Repeated Tension-Compression.

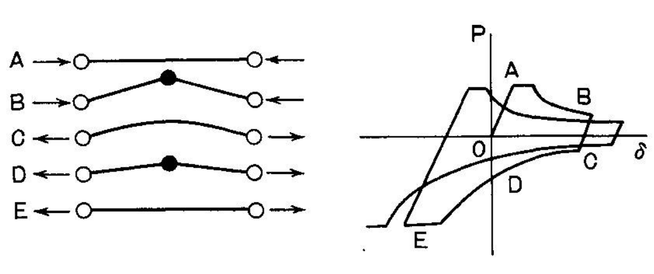

Fig. 6 Theoretical Hysteretic Behavior of a Bar under Repeated Tension-Compression.

As understood from Fig. 5, however, a bar does not recover a perfectly straight form at E, and consequently buckling load actually decreases. Therefore, in pursuing plastic hysteretic curve, it becomes necessary to establish more exact analytical method in which plastic deformations are taken into consideration.

Fig. 7 shows analytical results by non-linear analysis in which a bar is divided into discrete elements, and incremental displacements at arbitrary loading state are determined by numerical calculation based on the principle of stationality of potential energy.

It is seen that the reduction of resistance in post buckling appears differently depending on slenderness ratios and that buckling strength decreases in each loading cycle.

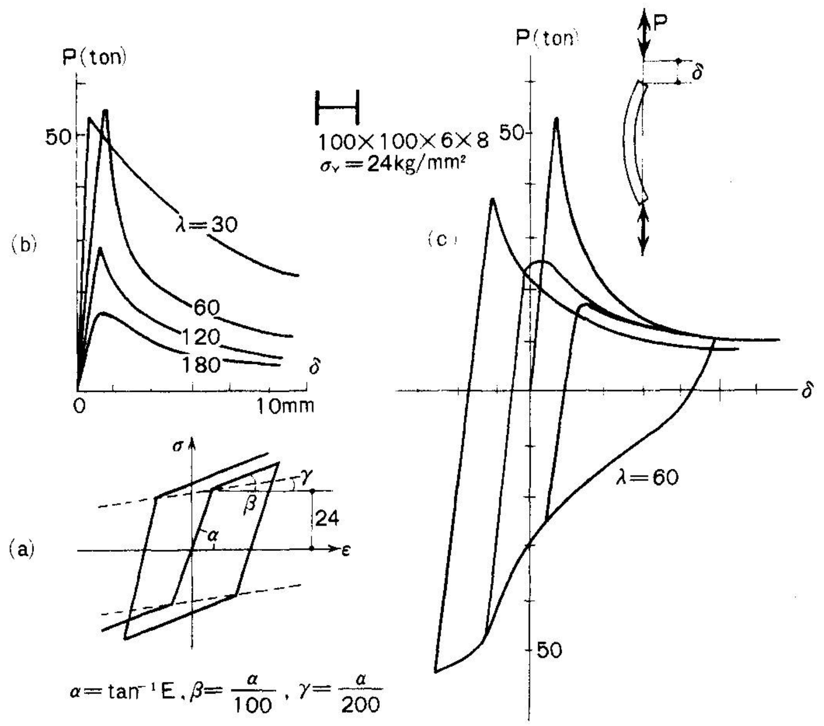

Fig. 7 Theoretical P-δ curves of a Bar under compression and Repeated Tension-Compression.

5. BEAMS AND COLUMNS

Fig. 8 shows load-deformation hysteretic curve of cantilevered beams subjected to repeated loading. The plateau exists in the virginal loading and in subsequent loadings the curves are quite stable. From the above results and as stated in Chapter 3, the local buckling of plate elements (in this case, flange) does not scarecely affect on the strength and the rigidity.[14),15),16),17)] A few experiments are undertaken for columns under repeated bending with constant axial force.[25), 26)]. Fig. 9 is an example of such experiment. From the above result, it is seen that in case large axial force exists, the height of the first curve is low and the gradients of the curves are negative after the attainment of maximum load in each loading cycle. This phenomenon is called P-Δ effect. It should be noted, however, that the load carring capacity is increasing in each loading cycle because of the accumulated compressional strains and strain hardening under repeated bending and constant axial force. This can be analyzed by assuming bi-linear relationship between stresses and strains.[25),26),27)]

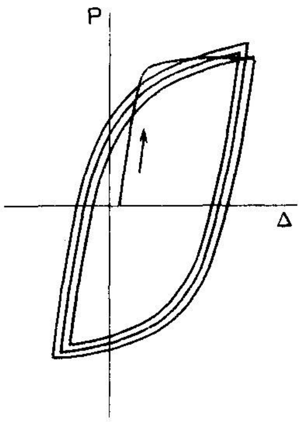

Fig. 8. Stability of Consecutive Hysteresis Loops

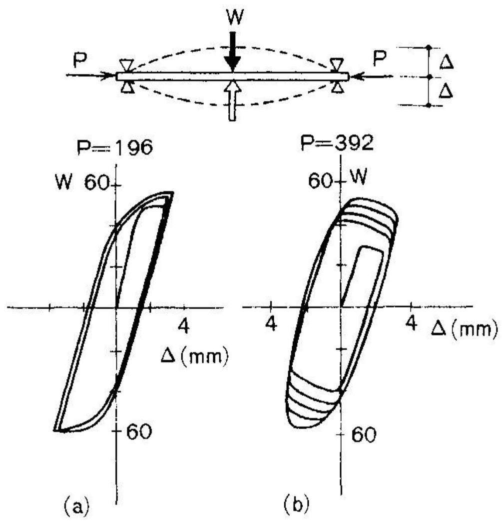

Fig. 9. Hysteresis Loops of Beam-Column under Repeated-Bending.

Fig. 10 shows one of the calculation results. Implied in the figure is that the system takes up more and more load under a constant amplitude of cyclic loading, and that the curves asymptotically approaches to the curve corresponding to that in no axial force.

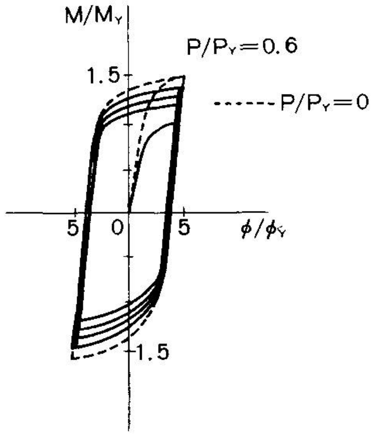

Fig. 10. Hysteresis Moment-Curvature Relationships of a Cross Section under Constant Axial Force.

Reference 28) presents the analytical moment-curvature hysteretic characteristic of a column under constant axial force and cyclic bending, by using stress-strain hysteretic characteristics of a simplified model which is subjected to one-sided repeated stressing. The analytical result is compared with experimental one of a column subjected to constant axial force and repeated pure bending.

Moreover, problems related to lateral buckling and lateral bracing of beams and columns under repeated plastic hysteresis are not systematically researched to date and are left for future investigations.

6. MECHANICAL FASTENERS AND WELDING

As the means of connections for steel structures, are used welding and mechanical fasteners, i.e. rivets, bolts and high-tensile bolts. The properties of fasteners and welded connections under repeated loading are in many cases verified indirectly through experiments in which these connections are used in members and in frames. As for rivets and bolts under repeated plastic hysteresis, the need is for studies concerning on relationship between bearing stress and deformations, characteristics of shearing deformation of fasteners and deformations of steel plate with holes and furthermore conditions of their failures. The property of frictional force are to be clarified for high-tensile bolts, and the investigation from the same viewpoint upon the materials as stated in Chapter 2 are necessary for welding.*1

7. CONNECTIONS

a. Beam-joints

Fig. 11 is one of the example of H-shaped beams under repeated loading, in which high-tensile bolted friction joint are employed.[14),30),31),32)] It is found out from experiments that once slip occurs at beam joint, slip load consecutively decreases as the numbers of cycles increase, and that the reduction of rigidity due to repeated loading are not significant.

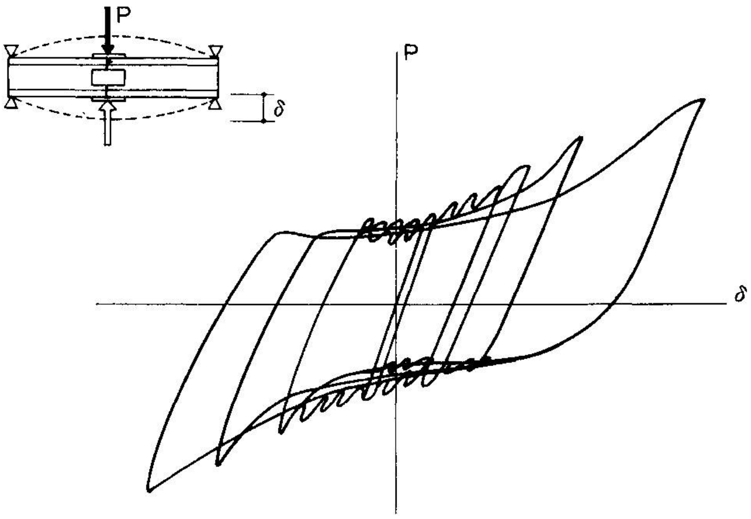

Fig. 11 P-δ curve of Wide-Flange Beam with High-Strength Bolted Joint.

b. Beam-to-column connections

Experiments on beam-to-column connections subjected to repeated load have been extensively undertaken, particularly, in Japan for various specimens as illustrated in Fig. 12. Throughout the various types of test's models, the reduction in rigidity at comparatively lower load has been recognized and has been a matter of concern. Its reason is now explained as that the panel zone, i.e.

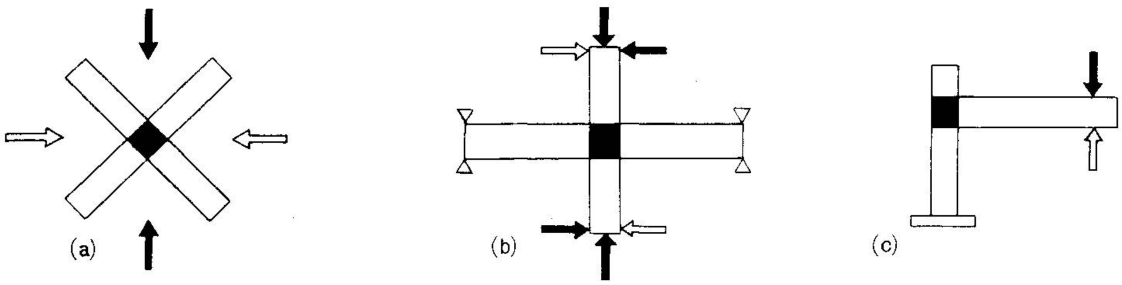

Fig. 12 Test Specimen of Beam-to-Column connection.

*1 See Ref. 29), for instance

column webs at beam-to-column connections yields early due to the existing large shearing force,[33),34),35),57)] and at present it is recommended to stiffen panel zone if necessary.

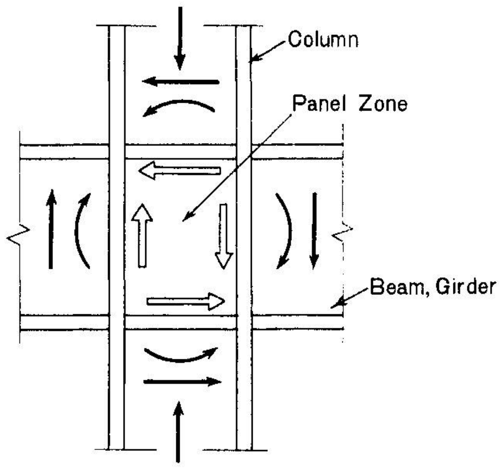

Fig. 13 Stress in the Panel zone.

c. **Column bases**

Although the column bases are important parts to transfer the stresses in the skelton to foundation, there are few investigations for column bases taking consideration of the action of repeated force, and are expected to be undertaken in near future.[55)]

8. UNBRACED FRAMES

There're fewer studies, both experimental and theoretical, on the hysteretic characteristics of unbraced frames than those on monotonic loading case. Some result are available of experiments done in U.S.A. and in Japan.[28),34) ~46),57)]

In general, this kind of investigation is to research elasto-plastic behaviors of rigid frames under various types of repeated loadings. In many cases, however, it is done, particularly, to know the restoring force characteristic of each floor in order to apply for the dynamical elasto-plastic design of multi-storied buildings. Restoring force characteristic is, as illustrated in Fig. 14, so called spring constant between adjacent particles representing the masses of each floor. Restoring force characteristic is much influenced by shearing force and additional bending moments to the columns due to existing axial force P and horizontal displacement Δ. The latter is called P-Δ effect, as already

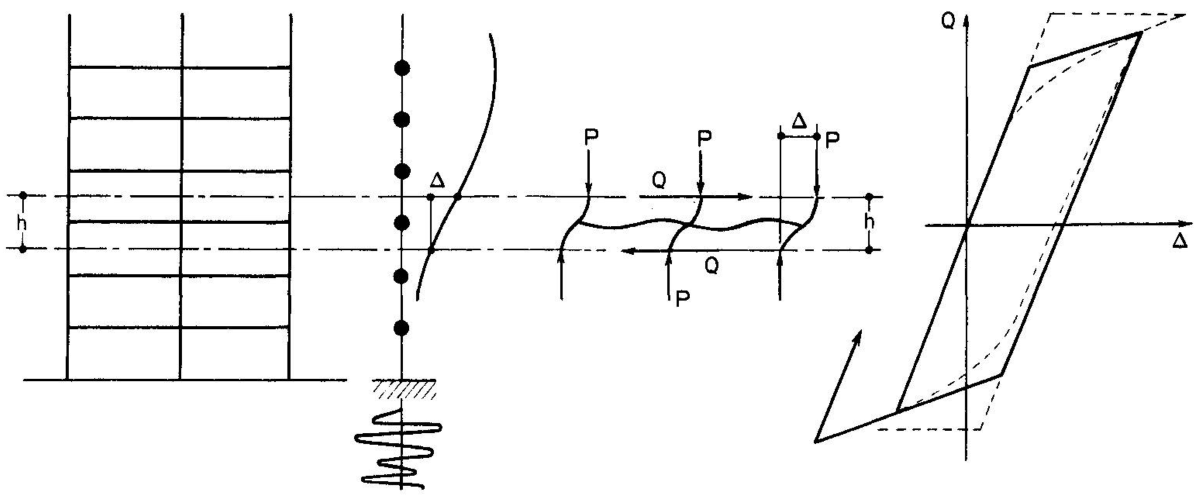

Fig. 14 Elastic-Plastic and Bilinear Type Restoring-Force Characteristics Used in the Seismic design.

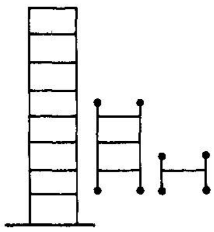

Fig. 15 Multi-Story Frames and tested Components.

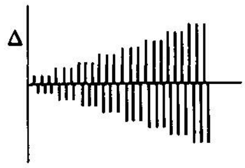

Fig. 16 Cycling Amplitude and Horizontal Displacement Program.

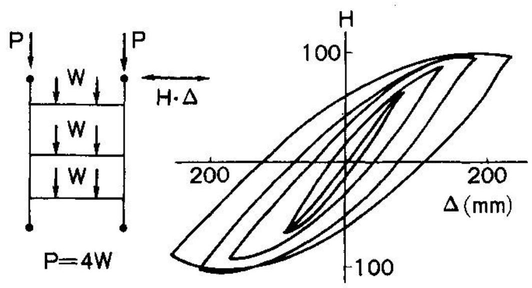

Fig. 17. Selected Load-Deflection Curves of a Frame under Repeated Horizontal Loading (P=4W).

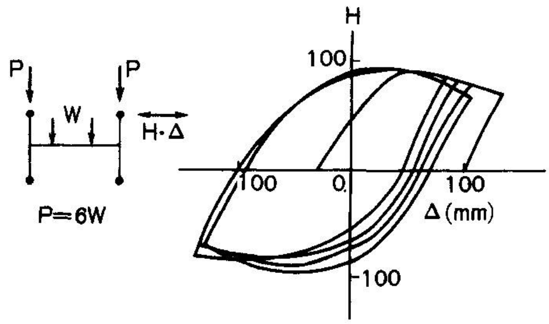

Fig. 18 Selected Load-Deflection Curve of a Frame under Repeated Horizontal Loading. (P=6W).

mentioned in Chapter 5. The stability of hysteretic curve is much influenced depending on the magnitude of P and Δ.

Reference 40) and 41) present full-scale test's results on three and one storied rigid subassemblages which are taken out of a multi-storied one-bay frame as shown in Fig. 15. Fig. 16 shows the test program of deflection amplitude which is gradually increased, and Fig. 17 and Fig. 18 are to show several cycles of hysteresis loops out of several ten of cycles. The conclusions deduced from the results are as follows:

1) Stability of loop is observed even at deflections after the maximum load is attained.
2) The maximum load that the frame can withstand is considerably greater than the theoretical prediction of the frame under monotonically increasing load.

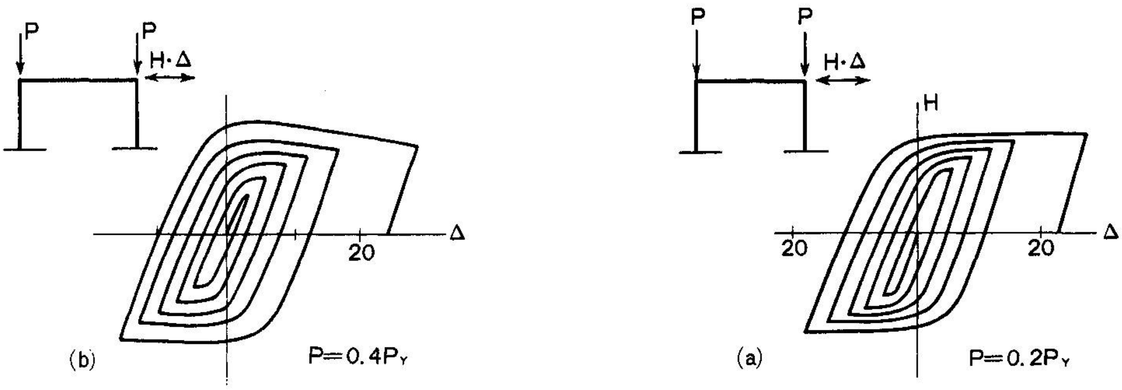

Fig. 19 Load Deflection Curve of Portal Frame under Repeated Horizontal Loading.

3) Strain hardening plays an important role after the attainment of the maximum load.
4) Hysteresis loops are influenced by yield zone at plastic hinges and the Bauschinger effect.

Shown in Fig. 19 are the results of small model tests with H-shaped cross section, indicating how the load carring capacity increases with the increase in vertical load P.[46),49)] Fig. 20 shows hysteresis curve obtained from tests of knee frames consisting of H-shapes in which a plastic hinge is formed at the column top.[47),48)]

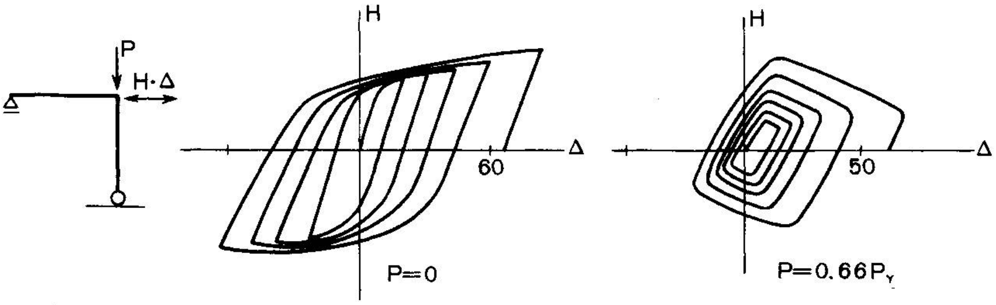

Fig. 20 Load Deflection Curve of Knee-Bents under Repeated Horizontal Loading.

From these results, plastic hysteretic curve of unbraced frames under the action of repeated horizontal loads is modeled as illustrated in Fig. 21, neglecting Bauschinger effect.[48)]

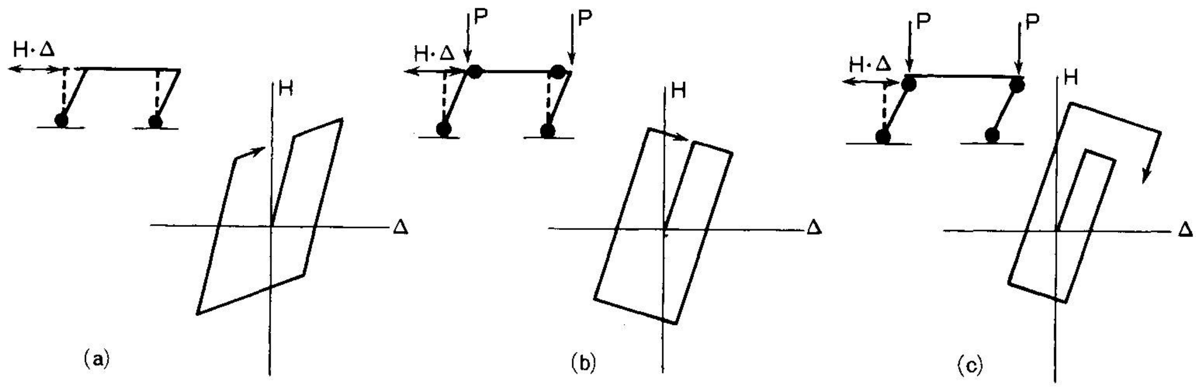

Fig. 21 Positive and Negative Bilinear Histeresis Curves of Portal Frames under Repeated Horizontal Loading.

a) In case that the vertical load P does not exist or are small, the plastic range of H-Δ curve are parallel to Δ-axis, neglecting strain hardening.
b) In case that the vertical load P is large and the collapse occurs at beam ends, H-Δ curve is modeled by closed loop with negative gradient in plastic range, due to P-Δ effect.
c) In case that the vertical load P is large and the collapse occurs in columns, H-Δ curve is modeled by helically expanding loops due to the accumulated compressive strains and strain hardening as stated in Chapter 5, with negative gradient in plastic range, due to P-Δ effect as in the case of b).

9. BRACED FRAMES

The restoring force of a braced frame is considered to be nearly equivalent to the summation of the restoring forces of both portal frame and bracing itself which is treated in Chapter 5. Therefore, the hysteresis loops are directly affected by the behavior of bracings and are completely different from those of unbraced frame.

There have been undertaken very few investigations into the behavior of braced frames under large amplitudes of repeated loading. Experiments were done on small models of rectangular cross section and of H-section, on medium-sized models of H-section, and on full-scale model of H-section, all with two diagonal bracing members.[36),37),38),46),48),49),52)] Some others were done on K-truss type frames, and on braced frames with only one diagonal bracing.[49),50),51),52),53),54)]

Fig. 22 was obtained from a small model test,[46),49)] and some simularity is found between Fig. 22(a), which is obtained from a test on a braced frame with one diagonal bracing, and the one shown in Fig. 5, which presents the behavior of the bracing itself.

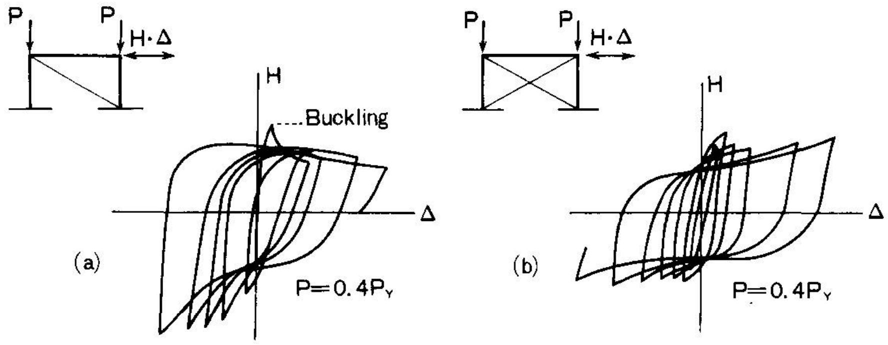

Fig. 22 Load Deflection Curves of Braced Portal Frames under Repeated Horizontal Loading

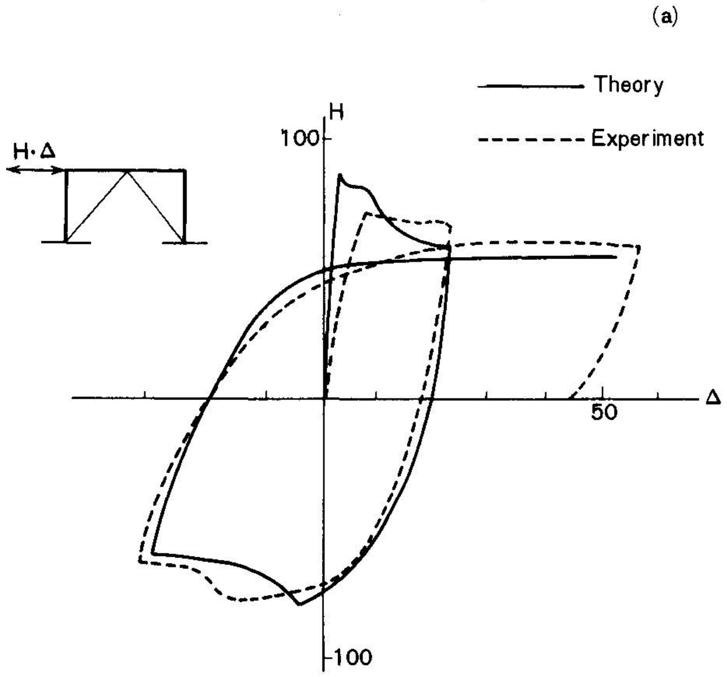

Fig. 23 Theoretical and Experimental Load Deflection Curves of a Braced Portal Frame under Repeated Horizontal Loading.

Fig. 23 shows comparison of experimental results,[54] on one-half model of a braced frame composed of H-shaped members subjected to repeated horizontal force to the theoretical analysis by discreate element method[24], already referred in Chapter 4, and the both results seem to be in a good agreement.

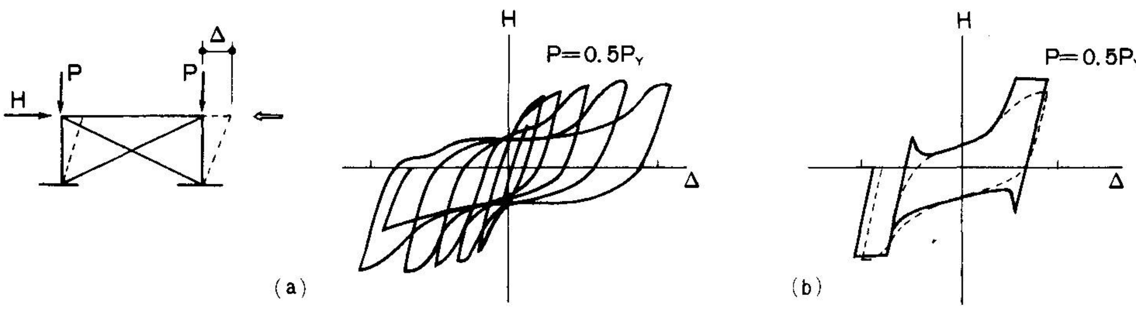

Fig. 24 Load-Deflection Curve of a Braced Full-Scale Portal Frame under Repeated Horizontal Loading

Fig. 24 is an example of the results obtained on a braced frame with two diagonal bracings.[48] Fig. 24(a) is the results on full-scale tests, the bracing members of which are a little more slender than those shown in Fig. 22(b). In Fig. 24(b), one cycle of the result is plotted by dotted line, and the solid line is the corresponding curve that is theoretically obtained, making use of the hysteresis curves in Fig. 6. As was mentioned related to Fig. 5, once large deflections occur due to buckling, the bracing member does not recover its straightness even though plastic elongation is given to it. The loop is rather round in this case. The theoretical curve seems to be in good agreement with the test's result.

A model of hysteretic curve of braced frames can be the one as diagrammatically illustrated in Fig. 25.

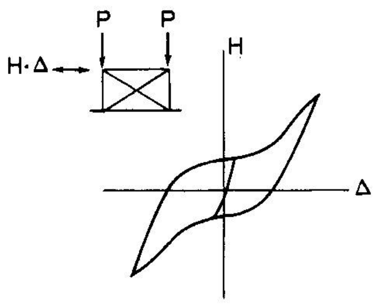

Fig. 25 S-Shaped Hysteresis Loop of a Braced Portal Frame under Horizontal Loading.

10. CONCLUSION

Concerning on the steel structures, their elements, their connections and their materials subjected to repeated force applied in quasistatic manner, are stated in this report various mechanical characteristics obtained mostly through experimental investigations. Here, are presented a brief summary for symposium discussion as reference idems.

(1) Mechanical properties of materials, steels and welding in particular – low-cycle fatigue

i) behavior of failure for steels and welded parts

a) necessity of criterion of failure for not only simply stressed states, but for combined stressed states

b) conditions for deterioration of notch toughness due to plastic strains
c) decrease in elongation capacity due to sectional discontinuity (influences of strain hardening and yielding-strength ratio)

ii) quantitative treatment on stress-strain relationship*1
a) lowering of proportional limit – Bauschinger effect
b) strain hardening
c) yielding-strength ratio

iii) characteristic of bearing stress for riveted and bolted connections and of frictional force in high-tensile friction joint

(2) Local buckling of plate elements

Influences of changes in material characteristics during loading cycles i.e., decrease of proportional limit and strain hardening

Necessity of establishment of width-thickness ratio on a basis of critical strain of buckling

(3) Bucklings and P-Δ effect

Understanding of various characteristics under repeated loading; Euler buckling, lateral buckling, lateral bracing and P-Δ effect, or compression members, beams and columns, including post buckling behaviors and considering the influences of strain hardening

(4) Connections

Establishment of various fastening systems and understanding of their mechanical characteristics under repeated loading in order to obtain rigid, ductile, tough connections

(5) Frames

Understanding of characteristics of histeresis loop considering P-Δ effect, reductions of maximum resistance and rigidity due to buckling of bracing and the influences of strain hardening

(6) Miscellaneous problems

Problems such as influence of imperfections existing in plate elements, members and frames, influence of residual stress and bi-axial bending of members, which was not dealt with in this report, are also challenging problems. Though damping and energy absorption capacity have close relationships with hysteretic characteristics of structures subjected to repeated force, such ploblems are extensively discussed in Theme II and are not dealt in this report.

In order to confirm a design method of earthquake resistant structures, it is essential as stated in Introduction to understand behaviors of structures subjected to repeated force. In this purpose, we should treat seismic loads, not as quasistatically repeated forces as discussed herein, but as semi-impulsive*2 and yet random dynamical ones.

Investigations on the basis of the aforementioned viewpoint, in fact, has just begun and many brains and efforts will be needed to secure a earthquake resistant construction of steel structures.

ACKNOWLEDGEMENTS

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*1 See Ref 6), for instance

*2 In Ref.56), influences of strain velocity and yielding-strength ratio of steels are discussed in case that sectional discontinuities such as holes and notch exist.

*3 Wakabayashi, M., : FRAMES UNDER STRONG IMPULSIVE WIND OR SENSMIC LOADING, State of Art Report No.5 Technical Committee, 5, 1972

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TECHNICAL RECOMMENDATION FOR HIGH-RISE BUILDINGS, (in Japanese)

SUMMARY

This report refers to various mechanical characteristics of steel structures, their elements, their connections and their materials under the action of statically repeated force, mainly obtained through experimental investigations, and extensively considers lowering of proportional limit of materials, low-cycle fatigue, local and primary buckling, P-Δ effects, behaviors of connections and frames, and miscellaneous problems.

RESUME

Ce rapport réfère à diverses propriétés mécaniques de constructions en acier, de leurs éléments, assemblages et matériaux sous l'action de charges statiques répétées. Les résultats obtenus proviennent essentiellement d'études expérimentales. Le rapport envisage la diminution de la limite élastique des matériaux, l'étude de la fatigue sous l'effet de cycles longs, du flambage local et primaire, des effets P-Δ, du comportement des assemblages et structures, ainsi que d'autres problèmes.

ZUSAMMENFASSUNG

Der Bericht bezieht sich auf verschiedene mechanische Charakteristiken von Stahlbauten, auf ihre Elemente, ihre Verbindungen und Materialien unter Einwirkung statisch wiederholter Kräfte. Sie wurden in der Hauptsache durch experimentelle Untersuchungen gewonnen und berücksichtigen weitgehend das Absinken der Elastizitätsgrenze der Materialien, die in längeren Zyklen wiederholte Ermüdung, sowie die örtliche und primäre Knickung, die P-Δ Effekte, das Verhalten der Verbindungen und Tragwerke, nebst weiteren Problemen.

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