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

Band: 10 (1976)

Artikel: Deformation capacity of high-strength steel members

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DOI: https://doi.org/10.5169/seals-10455

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Deformation Capacity of High-Strength Steel Members

Capacité de déformation d'éléments en acier à haute résistance

Verformungsfähigkeit von Gliedern aus hochfestem Stahl

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§1. INTRODUCTION

As large sized steel structures have been developed, high-strength steels having high yield stress level have attracted special interest recently. In this situation, it is becoming to be common to apply high-strength steel on the simple plastic design of structures. On the simple plastic design method, the steel structures must be able to maintain through a sufficient inelastic rotation without a decrease of moment capacity at each plastic hinge to allow the formation of a failure mecnanism. Then, the deformation capacity of members comes up as an important problems. Therefore, there are many difficult problems in using high-strength steel which is less ductile than that of low-alloy steels. There are, however, few reports on high-strength steels concerning the simple plastic design of structures, and not enough of the necessary basic data.

The objectives of this paper are to explain the plastic behavior of high-strength steel members, and to determine quantitatively the relationship between the rotation capacity and the material properties of steels.

§2. OUTLINE OF EXPERIMENTS

2.1 EXPERIMENTS

Experiments are made to explain plastic behavior and deformation capacity of beams and beem-column. Test speciments of beams are built-up H-250×125×12×12 and test speciments of beam-columns are built-up H-150×150×9×9. The kinds of steel used in this experiments are low-alloy steels (SM-41, SM-50) and high-strength steels (HT-60, HT-80). The loading conditions of beams are a uniform moment and a moment gradient, and that of beam-columns are axial load and one end bending moment. In addition to using four kinds of steels, bracing spaces and axial forces are varied, in order to investigate their influences on the rotation capacity of these steel members.

2.2 MATERIAL PROPERTIES

The material properties of each steels are determined by tension tests and stub column tests with wide-flange shape. Yield stress level of high-strength steel has higher level, comparing low-alloy steel. Yield stress level of SM-41 is evaluated $3.24t/cm^2$, and that of HT-80 is evaluated $8.80t/cm^2$. The yield plateau length is short and the stress strain curve of HT-80 shows the stiff bilinear material. The strain hardening modulus Est is smaller than that of SM-41. Additionally, the yield ratio and elongation of the material are small. These results of each materials are showed in Table-1. The ductilities of material of high-strength steel are small as is obvious from Table-1. There are many difficult problems in applying high-strength steel on the plastic design fo steel frames.

§3. EXPERIMENTAL RESULTS

3.1 LOAD-DEFLECTION CURVES

Fig. 1 ∿ 3 show the experimental load-deflection curves. Moments and rotation angles have been nondimensionalized with full-plastic moment Mp and rotation angle Θpc are used. Fig. 1 shows the load-deflection curves of beams under uniform moment. Moment reaches at full-plastic moment. Except HT-80, moment remains at near-constant value Mp and the in-plane deformations increase. This plastic behaviors are not influenced with the kinds of steel. Fig. 3 shows the load deflection curves of beams under moment gradient. These plastic behaviors are different from the beams under uniform moment. The plastic behaviors are effected with the strain hardening modulus and the plastic plateau length of material. Moments increase exceeding full plastic moment. In general, the strain hardening modulus has effects upon the rigidity of members after yielding. If the plastic plateau length is small, the effects of strain hardening modulus on plastic behaviors are remarkable. As the plastic plateau length decreases, the deformations of members at the same moment level are small. Fig. 4 shows the load deflection curves of beam-columns. In this case, the plastic behaviors are similar to that of beams under moment gradient.

3.2 LATERAL BUCKLING AND LOCAL BUCKLING

Fig. 4 ∿ 6 show the strain distributions as the moments decrease due to local or lateral buckling. Fig. 4 shows the strain distributions along the axis of members at two points of Mp and the decrease of moment. When moments reach at Mp, the strain distributions are not uniform along the axix of members. The strain distribution of HT-80 are uniform and the level of strain is about the strain hardening level εst. Because the strain hardening modulus is small, the moment decreases rapidly. In the case of beams under uniform moment, the main cause of decrease of moment is the increase of torsional deformation. Fig. 5 shows the strain distributions of beams under moment gradient. The distributions are different from that of beams under uniform moment. On high-strength steel, the yield length is shorter than that of low-alloy steel and the gradient of strain distributions is large. On the beams under moment gradient, the local buckling causes the dropping of the applied load. Fig. 6 shows the curvature distributions along the axis of beam-columns and the strain distribution at the decrease of moment. Maximum curvature point moves to center from the end of span as the axial force increases. The behaviors at the decrease of moment are different each other due to the point of maximum moment. When the maximum moment occurs at the end of the beam-columns, strain distributions are uniform and diformations of out of plane are not recognized and the beam-columns have enough deformation capacity. These results show that the plastic behaviors of the beam-columns are same as the beam under moment gradient.

3.3 RELATION OF DEFORMATION CAPACITY AND MATERIAL PROPERTY

The deformation capacity of steel member is influenced with the material properties. Fig. 7 and 8 show the rotation capacity and slenderness ratio relationships of beam. It is clearly that each rotation capacities are different due to the material properties. In Fig. 7 and 8, the curves show the following equations[9] These equation are obtained from the analysis assuming two models.

Two models are based on the following ideas that are obtained from the experimental behavior. The lateral buckling and local buckling determine the limit of the deformation capacity.

Under uniform moment

$$R = K_1 \frac{1}{\lambda_y^2} (\sigma y\dot{o}/\sigma y)^2 \sqrt{\frac{B}{H}} \quad (1)$$

Under moment gradient

$$R = K_2 \frac{1}{\lambda_y^2} \rho(\sigma yo/\sigma y)(\frac{t_f}{B}) \quad (2)$$

Fig. 9 shows the load-deflection curves of beam-columns which have same slenderness ratio (λ_x=30) and various axial force. Fig. 10 shows the relations of the rotations capacity and axial force with the slenderness ratio as a parameter. The curves in this figure are obtained from the numerical analysis according to the finit element method. Fig. 1 shows the critical slenderness ratio of beam-columns and experimental results. The rotation capacity of beam-columns is influenced with the axial force, the slenderness ratio and material properties. Especially, the deformation capacity of beam-columns is influenced more significantly with material. High-strength steel beam-columns (HT-60, HT-80) have few the rotation capacity. The curves in this figure show the critical slenderness ratio of beam-columns having enough rotation capacity. The thick solid line shows the critical value which can ensure the rotation capacity above R=3 due to the numerical analytical results. This result is agreement with the experimental results. Specification of AIJ is loose in order to have enough rotation capacity. From these results, the following critical slenderness ratio that is proposed by Lay, M.G.[6] is equivalent to the experimental results.

$$P/Py = \frac{1 - \bar{\lambda}}{1 + \bar{\lambda}} \quad (3)$$

§4. CONCLUSION

In this paper, the deformation capacity of steel members is explained by the experiment and numerical and theoretical analysis. In general, high-strength steel is seemed to be disadvantageous applying on the simple plastic design of steel structures which requires the enough rotation capacity. Especially, it is worth noting that HT-80 having the stiff bi-linear material curve used in this experiments has few deformation capacity. The rotation capacity is directly influenced by the value of yield stress, the plastic plateau length and the strain hardening modulus. Therefore, we conclued that the effective factors can be represented only by the ratio of yield stress. The rotation capacity is proportional to the square of the reciprocal ratio of yield stress in the case of uniform moment, and to the reciprocal ratio of that in the case of moment gradient. On the beam-columns, the redundant of rotation capacity is remarkable due to the material properties.

ACKNOWLEDGEMENT

In writing this paper the authors are grateful to Sumitomo Metal Industries, Ltd. for providing the test speciments of high-strength steel. Especially, the authors wish to thank Mr. Y. Nishida and Mr. M. Kato of Sumitomo Metal Industries, Ltd..

Table 1 Material Property

STEEL•	THICKNEESS (mm)	σ_y (t/cm²)	σ_u (t/cm²)	ε_y (×10⁻⁶)	S ($\varepsilon/\varepsilon_y$)	$E\times10^3$ (t/cm²)	E_{st} (t/cm²)	σ_u/σ_y	h (E/E_{st})	Elong. (%)
SM-41	12	3.24	4.76	1521.	13.8	2.13	47.0	1.47	45.3	28.5
SM-50	12	3.95	5.53	1855.	10.6	2.13	36.1	1.40	59.0	23.4
HT-60-1	12	5.78	6.78	2706.	6.78	2.14	31.0	1.17	69.0	26.6
(HT-60-2)	(12)	(5.45)	(6.65)	(2547.)	(5.89)	(2.14)	(36.4)	(1.20)	(58.0)	(30.7)
HT-80	12	8.80	9.39	4112.	1.00	2.14	15.0	1.07	142.7	24.4

•TEST COUPON DIMENSION (JIS Z 2201) SM-41, SM-50……No. 1 TEST COUPON
HT 60, HT 80……No. 5 TEST COUPON

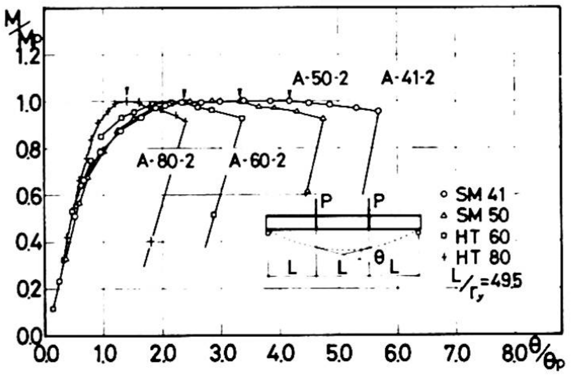

Fig.1 M–Θ Relationships

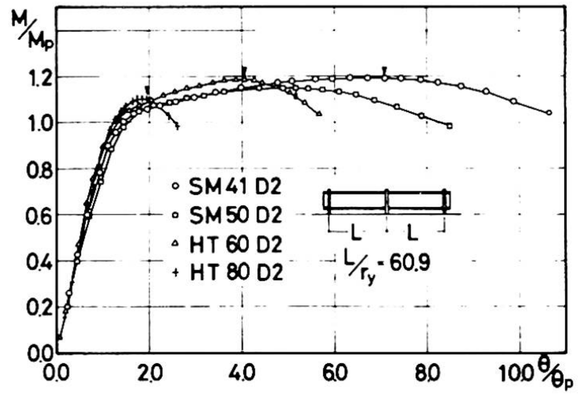

Fig.2 M–Θ Relationships

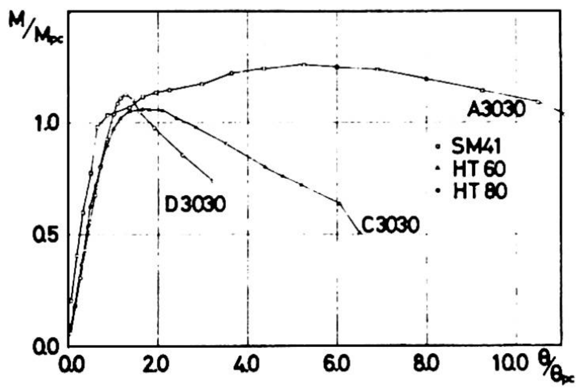

Fig.3 M–Θ Relationships

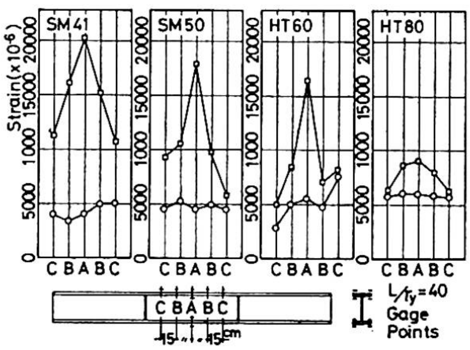

Fig.4 Strain Distribution

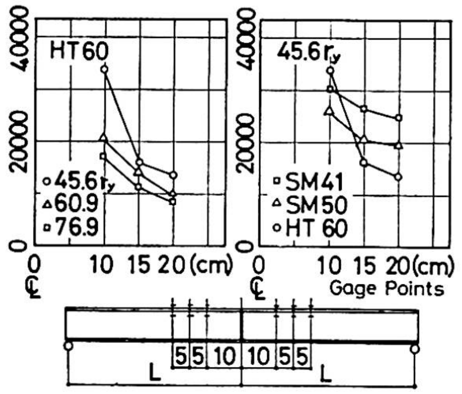

Fig.5 Strain Distributio

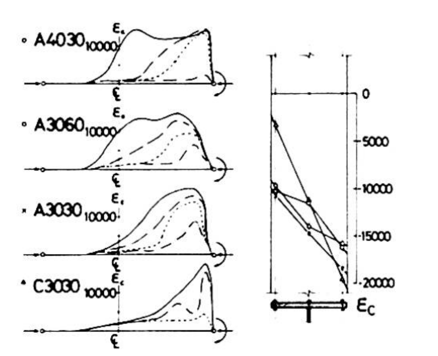

Fig.6 Strain Distributio

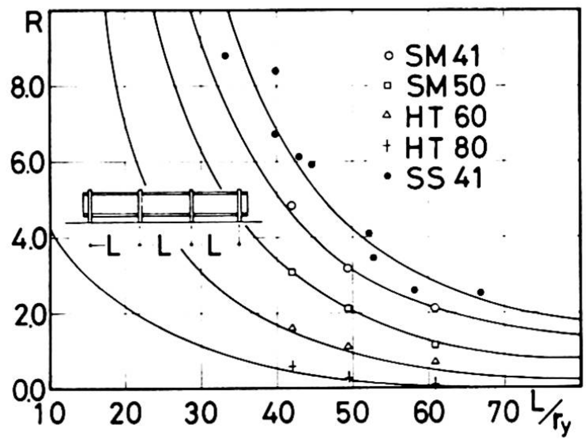

Fig.7 Rotation Capacity

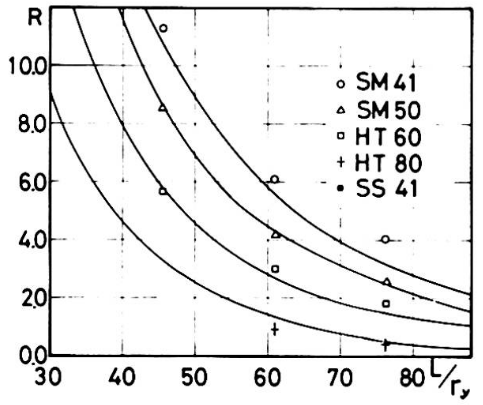

Fig.8 Rotation Capacity

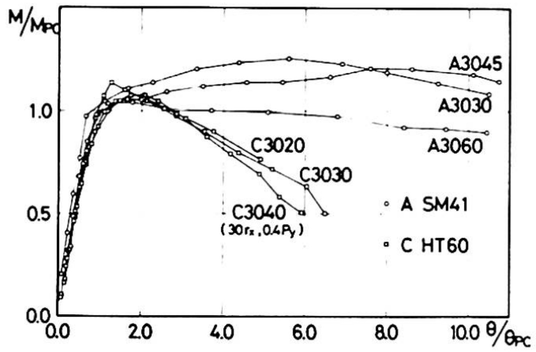

Fig.9 M-Θ Relationships

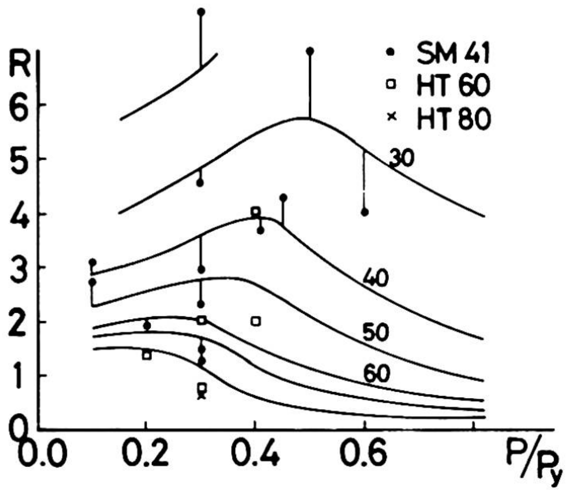

Fig.10 Rotation Capacity

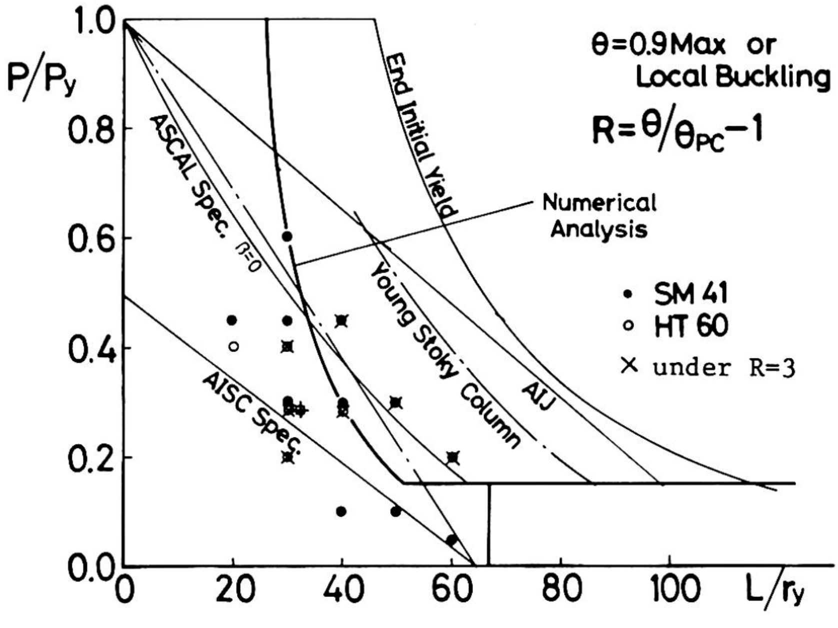

Fig.11 Critical Slenderness Ratio

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SUMMARY

The plastic behaviour and the deformation capacity of high-strength steel members are discussed on the relation to the low-alloy steel members. High-strength steels seem to be disadvantageous applying on the simple plastic design of steel structures. Especially, it is worth noting that HT-80 used in this experiment has few deformation capacity. While the rotation capacity is directly influenced by the value of yield stress, plastic flow and strain hardening rigidity, we conclude that the effective factors can be represented only by the ratio of yield stress.

RESUME

Le comportement plastique et la capacité de déformation d'éléments en acier à haute résistance sont comparés avec ceux de l'acier doux. Il semble que les aciers à haute résistance sont désavantageux lors du calcul plastique simple de structures en acier. Il faut remarquer que l'acier HT-80 employé dans cette expérience a une faible capacité de déformation. La capacité de rotation d'éléments en acier est directement influencée par la valeur de l'effort à la limite d'écoulement, l'écoulement plastique, et le durcissement par déformation. D'autre part nous concluons que ces facteurs efficaces peuvent être représentés seulement par le rapport d'efforts à la limite d'écoulement.

ZUSAMMENFASSUNG

Plastische Verhalten und Verformungsfähigkeit von Gliedern aus hochfestem Stahl werden in Beziehung zu denselben von Gliedern aus Stahl St 37 diskutiert. Es scheint, dass hochfeste Stähle bei Anwendung der einfachen plastischen Berechnung von Stahlbauten nachteilig sind. Bemerkenswert ist, dass in diesem Experiment HT-80 eine geringe Verformungsfähigkeit zeigt. Die Rotationsfähigkeit von Gliedern aus Stahl werden unmittelbar durch die Höhe der Fliessgrenze, die Fliessverformung und die Steifigkeit im Verfestigungsbereich beeinflusst. Anderseits kommen wir zur Ueberzeugung, dass diese wirksamen Faktoren nur durch das Verhältnis der Fliessgrenzen dargestellt werden können.