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BUCKLING STRENGTH OF STEEL MEMBER HAVING ROTATIONAL SPRINGS AT ITS BOTH ENDS

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ABSTRACT

To investigate mechanical performance of compression member in truss structure,representing the contribution of elastic stiffness offered by abutting members(diagonal member and chord member) by providing with rotational restraints at both ends of compression members,cyclic load tests were carried out on simple member by using spring at their ends. Elasto-plastic analysis were also performed on truss structure. Consequently,it was found out that treating compression members in a structural framework as integral parts of the structure,rather than as isolated members with pin-ended,to archive a completely rational design of compression members.

KEYWORDS

buckling; rotation constrain; slenderness ratio; diagonal member; chord member

INTRODUCTION

As structural failures resulting from the buckling of a member in compression in a truss structure are brittle failures, it is important to design truss structures so as to eliminate such structural failures. So far, much work on the structural properties of the member in compression has been directed toward the elucidation of the behavior of a single member with its both ends in a simply supported condition as shown in Fig. 1-(a) by experiment or by analysis. However, the members in compression in full-scale truss structures are subject to the effects of abutting members, such as constraint of rotation, as shown in Fig. 1-(b). The present paper describes the results of the repeated loading test of a member with elastic rotation springs at its ends as shown in Fig. 1-(c) which was conducted to reproduce the effect of the elastic stiffness of the abutting members.

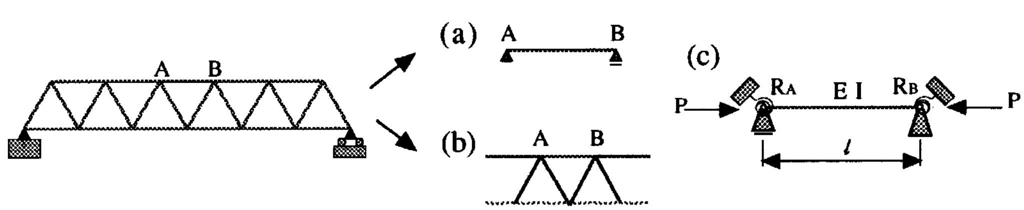

Fig.1. Estimation of end restraints

Moreover, the large deflection elastic-plastic analysis of the whole truss structure was conducted to study the effect of the abutting members on the member which may buckle.

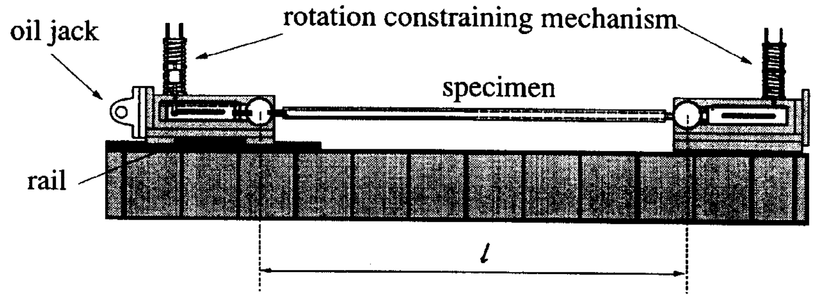

Fig.2. The loading apparatus used for the test

Table.1. The results of the mechanical properties

diameter (mm)	specimen	elastic stiffness (t/cm2)	yield stress (t/cm2)	tensile strength (t/cm2)
48.6	A-1	1968	4.26	4.47
	A-2	1974	4.56	4.59
average		1971	4.41	4.53
60.5	B-1	2021	4.19	4.64
	B-2	2111	4.28	4.62
average		2066	4.23	4.63
76.3	C-1	2096	4.18	4.91
	C-2	2180	4.22	4.91
average		2138	4.20	4.91
89.1	D-1	2087	3.89	4.31
	D-2	2203	3.47	4.25
average		2145	3.68	4.28

Table.2. Specimens

model	D(mm)	t(mm)	A(cm2)	I(cm4)	i(cm)	l (cm)	α ex	λ
AL-0							0.00	186
AL-1	48.6	3.2	4.564	11.82	1.61	300	0.95	162
AL-5							4.72	123
BL-0							0.00	148
BL-1	60.5	3.2	5.760	23.72	2.03	300	0.99	129
BL-5							4.63	98
CL-0							0.00	116
CL-1	76.3	3.2	7.349	49.18	2.59	300	1.03	101
CL-5							4.49	77
DL-0							0.00	99
DL-1	89.1	3.2	8.636	79.76	3.04	300	0.98	86
DL-5							4.32	65
DS-0							0.00	66
DS-1	89.1	3.2	8.636	79.76	3.04	200	0.97	57
DS-3							2.59	44

· NOTATION

AL-0 A : series、L(S) : specimen length (L=300cm,S=200cm)、0 : rotation spring constant(0 : no-spring、1 : α=1、5 : α=5、3: α=3)

· D : diameter t : thickness A : Section Area I : moment of second order i : radius of gyration l : specimen length α ex : measured value of α λ : equivalent slenderness ratio

OUTLINE OF TEST

Test plan

The loading apparatus used for the test is shown in Fig. 2. Steel pipes of 48.6, 60.5, 76.3 and 89.1 mm in diameter as shown in Table 2 were selected for specimens. Using these pipes, twelve specimens of 300 cm in length were prepared under three different conditions of elastic rotation constraint, i.e., both ends simply supported (α= 0) and under other two conditions defined by the following equation:

$$R_A = R_B = \alpha \frac{EI}{\ell}$$

For the specimens of 200 cm in length and 89.1 mm in diameter which correspond to the full-scale members with a small slenderness ratio, three specimens under three different conditions of constraint, i.e., α = 0, 1 and 3, were prepared. Using 50 tf double-acting oil jacks, incremental repeated loading test was conducted for the 15 specimens. Prior to this test, tensile test of the standard specimens getting from steel pipe was performed to determine the yield stress and tensile strength. The results of the mechanical properties test are shown in Table 1.

Rotation constraining mechanism at an end of the specimen

The rotation constraining mechanism installed at an end of a specimen is schematically shown in Fig. 3. In this mechanism, the elastic rotation spring at an end of the member which is shown in Fig. 1 is reproduced by attaching an arm to the node connected to the specimen and installing a spring at a distance L from the center of rotation of the node. To obtain the rotation spring constants at a = 1, 3 and 5, two kinds of springs were used.

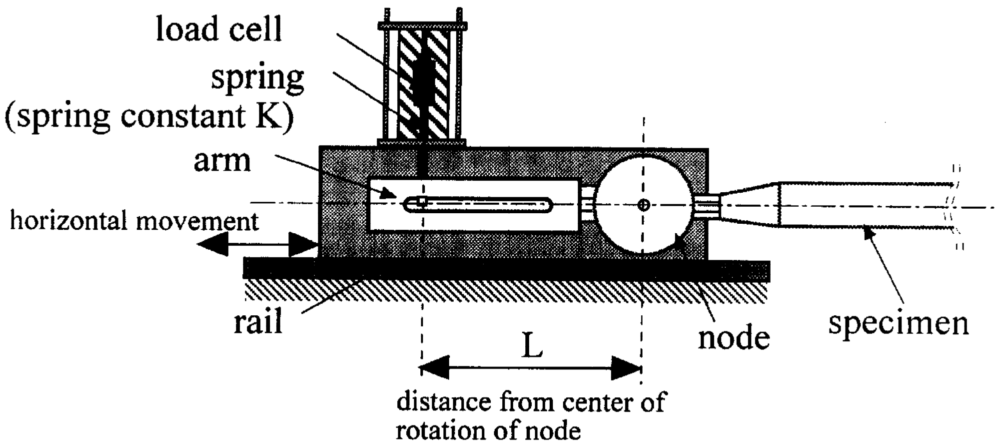

Fig.3. Rotation constraining mechanism

RESULTS OF TEST

Rotational stiffness

The rotational stiffness measured during test is lower than the calculated value because of the effect of the deformation of the arm and steel plate in the rotation constraining mechanism. The measured values of a (a_{ex}) are shown in Table 2.

Table.3. The results of test

model	λ	λ / λ y	Pex(t)	Pe(t)	Py(t)	Meb(t*cm)	Mea(t*cm)	Meb/My (%)	Mea/My(%)	My(t*cm)	Mp(t*cm)
AL-0	186	2.82	2.3	2.52	(20.13)	0.0	0.0	0.0	0.0		
AL-1	161	2.44	3.3	3.37	(20.13)	1.77	4.72	8.26	22.00	21.43	29.09
AL-5	126	1.90	6.1	5.56	(20.13)	5.80	11.71	27.06	54.64		
BL-0	148	2.14	5.3	5.32	(24.36)	0.0	0.0	0.0	0.0		
BL-1	127	1.84	6.7	7.19	(24.36)	3.50	5.27	10.55	15.89	33.16	44.44
BL-5	99	1.43	10.1	11.91	(24.36)	14.14	17.13	42.64	51.66		
CL-0	116	1.63	10.0	9.17	(30.87)	0.0	0.0	0.0	0.0		
CL-1	99	1.40	14.8	12.34	(30.87)	6.93	13.20	12.79	24.36	54.18	71.82
CL-5	79	1.11	18.5	19.63	(30.87)	8.62	22.10	15.91	40.79		
DL-0	99	1.32	18.7	18.74	(32.64)	0.0	0.0	0.0	0.0		
DL-1	85	1.13	20.8	25.57	(32.64)	3.98	25.70	6.04	39.02	65.87	86.9
DL-5	68	0.91	24.2	(−)	32.64	16.56	38.70	25.14	58.75		
DS-0	66	0.88	21.0	(−)	32.64	0.0	0.0	0.0	0.0		
DS-1	57	0.76	24.6	(−)	32.64	1.71	41.30	2.60	62.70	65.87	86.9
DS-3	49	0.65	28.9	(−)	32.64	5.67	46.40	8.61	70.44		

λ : equivalent slenderness λ y : crytical slenderness Pex : buckling load(experiment) Pe : Euler's buckling load

Py : yield force Meb : moment at the end of member before buckling Mea : moment at the end of member after buckling

My : yield moment(non-axial load) Mp : full plastic moment

Buckling strength

Figs. 4(a) ~ (d) show the experimentally determined axial load versus axial displacement in the cycle in which buckling was caused, together with the analytical values obtained by using the analytical model with the similar rotation constraint. It is apparent from these figures that the buckling strength determined by test agrees well with the analytical values.

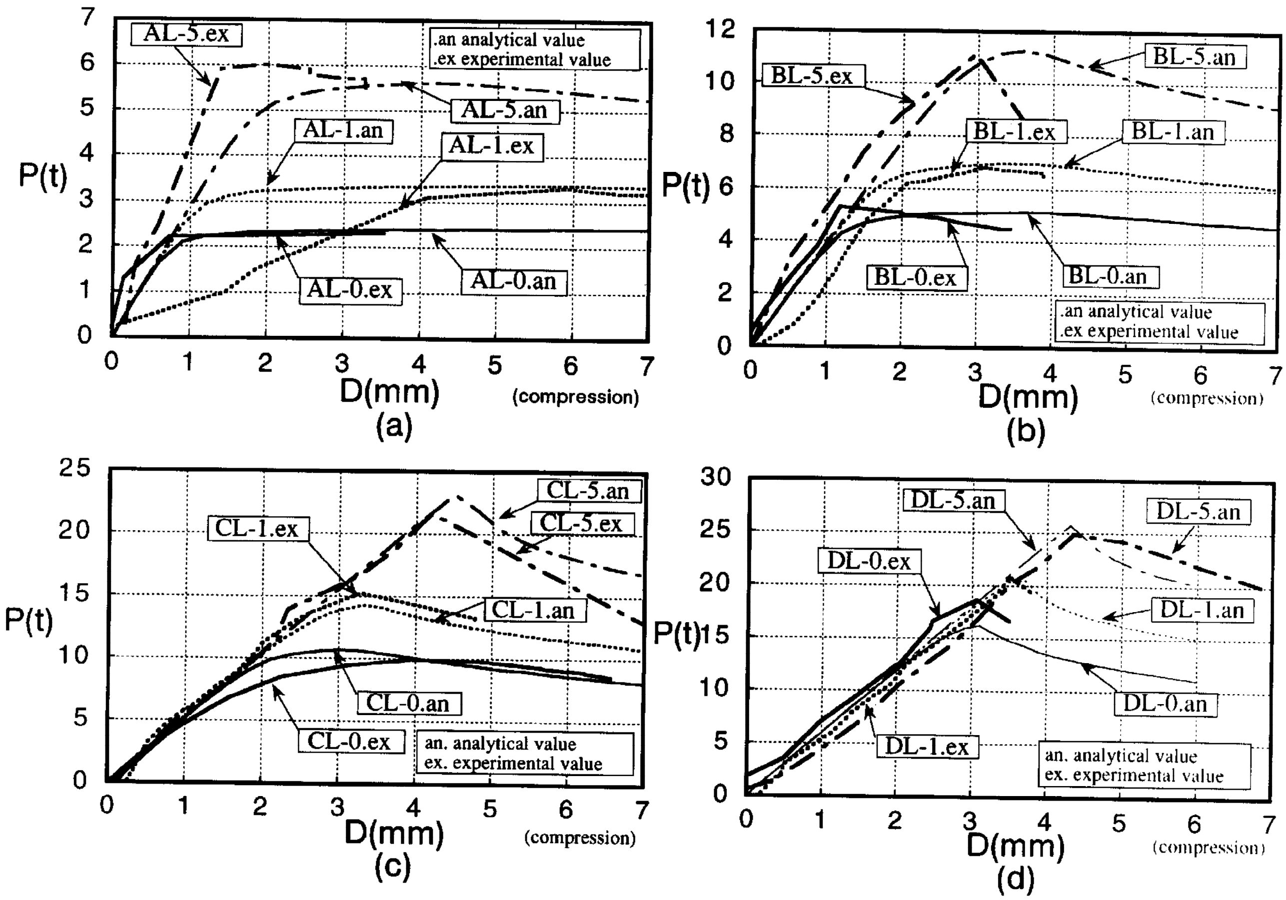

Fig.4. Load - axial displacement relation

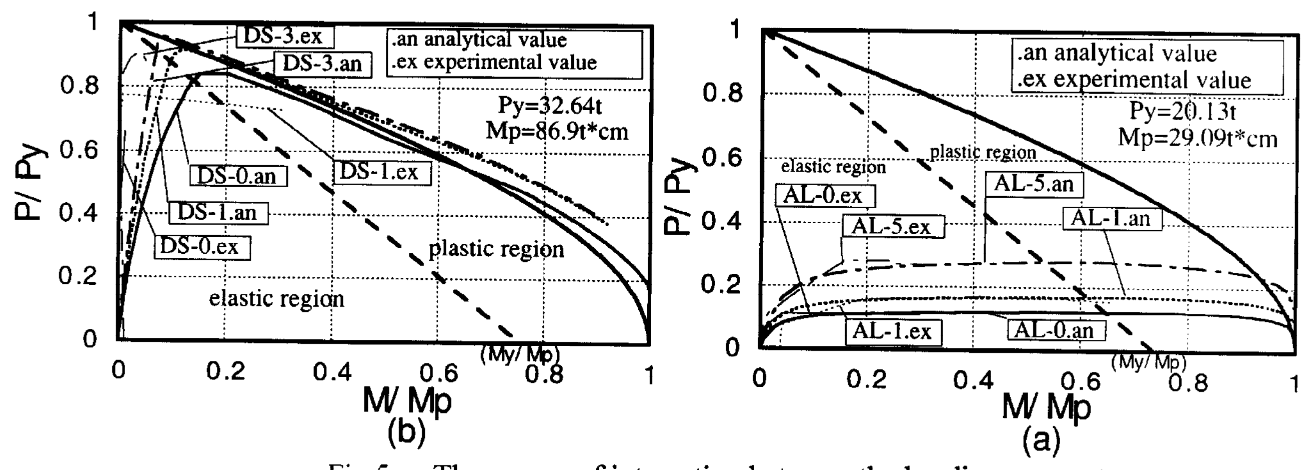

Fig.5. The curves of interaction between the bending moment and axial force in the middle of specimens

The results of test are shown in Table 3. A comparison of the specimens having the same member length and the same pipe diameter shows that the ratio of the moment at the end of the member (M_{eb}, M_{ea}) to the yield moment (M_y) before and after buckling increases with decreasing equivalent slenderness ratio of the specimen. Because of the effect of constraint by the rotation spring, the bending moment is induced in a direction in which buckling deformation is suppressed, and therefore the buckling strength increases.

Fig. 5 shows the curves of interaction between the bending moment and the axial force in the middle of AL and DS series specimens. These curves are normalized by the full plastic moment (Mp) and yield axial force (Py). The comparison of the curves reveals that the softening ratio of the specimens with lower slenderness ratio increases sharply after buckling. With the DS series specimens, all values of buckling strength are in the plastic buckling region. It is, therefore, apparent that the increasing ratio of buckling strength due to rotation constraint decreases.

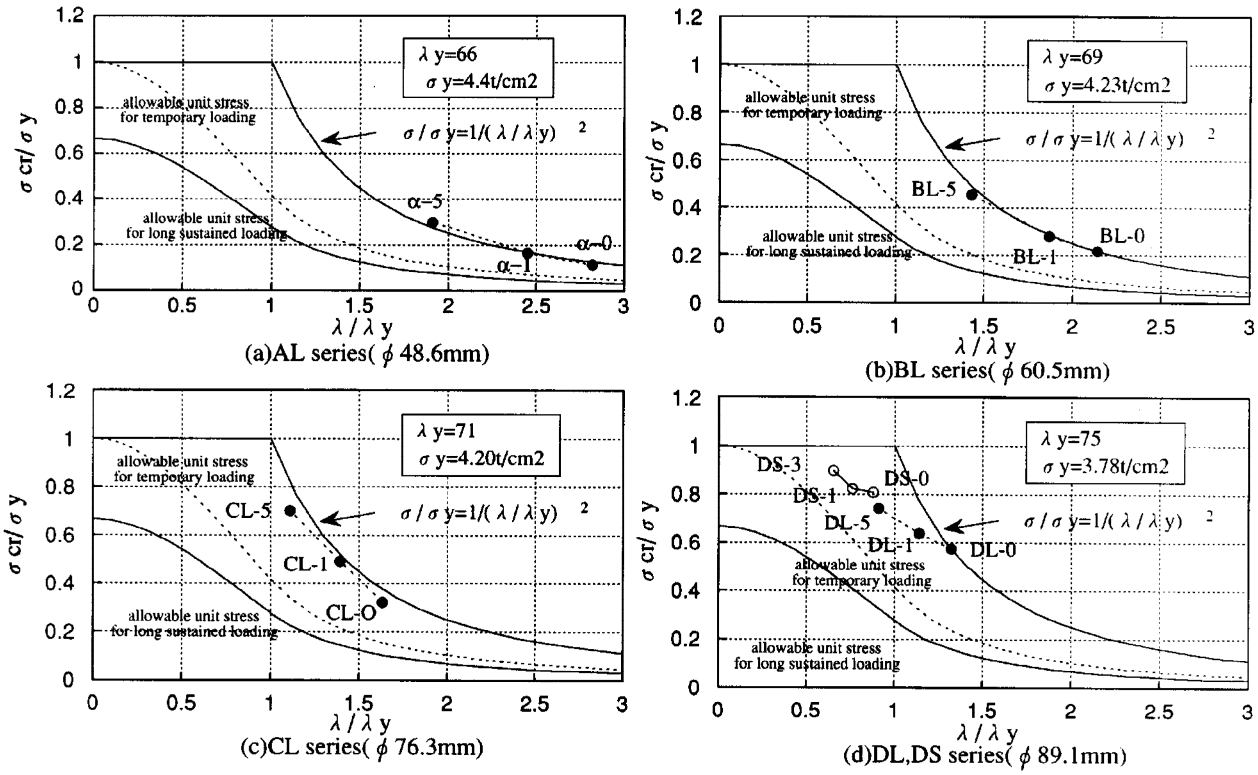

Fig.6. Evaluation by equivalent slenderness ratio

EVALUATION BY EQUIVALENT SLENDERNESS RATIO

The equivalent slenderness ratio (l) in which the buckling stress (s_{cr}) determined by test and the respective conditions of rotation constraint are taken into consideration was normalized by the yield stress (s_y) and critical slenderness ratio (l_y), the results of which are shown in Fig. 6. As the buckling strengths of the specimens with high slenderness ratio are in the region of elastic buckling, these strengths almost fit the Eular curve which is a theoretical curve. As the buckling strength enters the region of plastic buckling and deviates from the Eular curve as the slenderness ratio decreases, the increasing ratio of buckling strength due to rotation constraint decreases.

ANALYSIS OF TRUSS STRUCTURE

In the test, the effect of abutting members was reproduced by installing springs at both ends of the specimen, thus clarifying the behavior of the member in compression in a truss structure by testing a single member. To clarify the effects of respective abutting members (diagonal members and chord members), the large deflection elastic-plastic analysis of the whole truss structure was conducted[(1), (2)] with the sizes of diagonal and chord members as the parameters and studying the effect of abutting members on the buckling strength of the member in compression was studied. The analytical model used is shown in Fig. 7. The truss 0 is the standard model and the member 6-8 is assumed to buckle. For the diagonal 1 and 2 and the chord 1 and 2, the members are selected as shown in Table 4 and Fig. 8 to study the effects of diagonal and chord members, respectively. The chord 1 is the model in which the buckling strength of the member 6-8 is assumed to be nearly equal to that of the abutting members (4-6 and 8-10). The chord 2 is the model in which the abutting members (4-6 and 8-10) are assumed to buckle before the member 6-8 does. It is assumed that the downward initial deflection corresponding to 1/400 of the member length occurs in the member 6-8 only. Fig. 9 shows the relation between the load and the axial displacement of the buckling member. Fig. 10 shows the ratios by which the moments at the end of the buckling member 6-8 at the node 6 under the maximum load and before and after the application of the maximum load (90% of the max. load) are shared by the abutting members (4-6, 5-6 and 6-7).

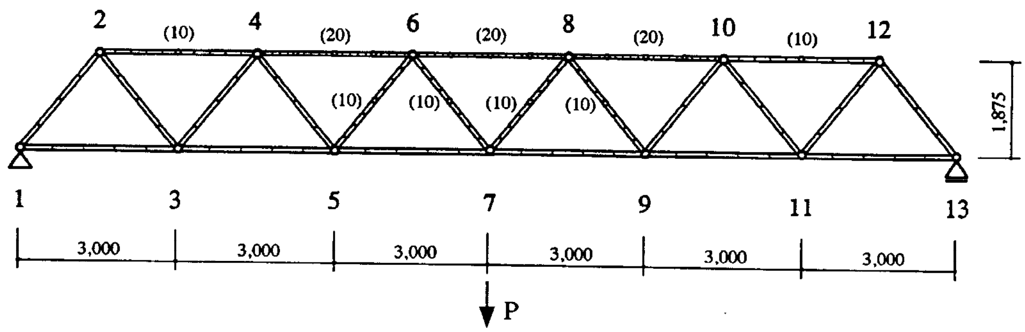

Fig.7. Analytical model

Table.4. Member of analytical model

analytical model	sign	chord member		diagonal member	
		D(mm)	t(mm)	D(mm)	t(mm)
truss 0	T0	89.1	3.2	60.5	3.2
diagonal 1	D1	89.1	3.2	89.1	3.2
diagonal 2	D2	89.1	3.2	48.6	3.2
chord 1	C1	—	3.2	60.5	3.2
chord 2	C2	—	3.2	60.5	3.2

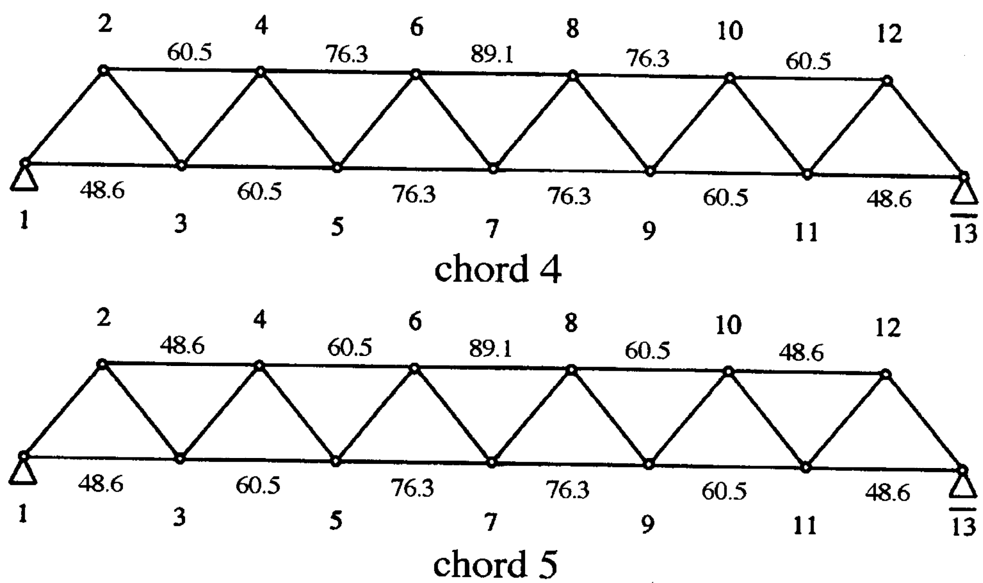

Fig.8. analytical model (chord member)

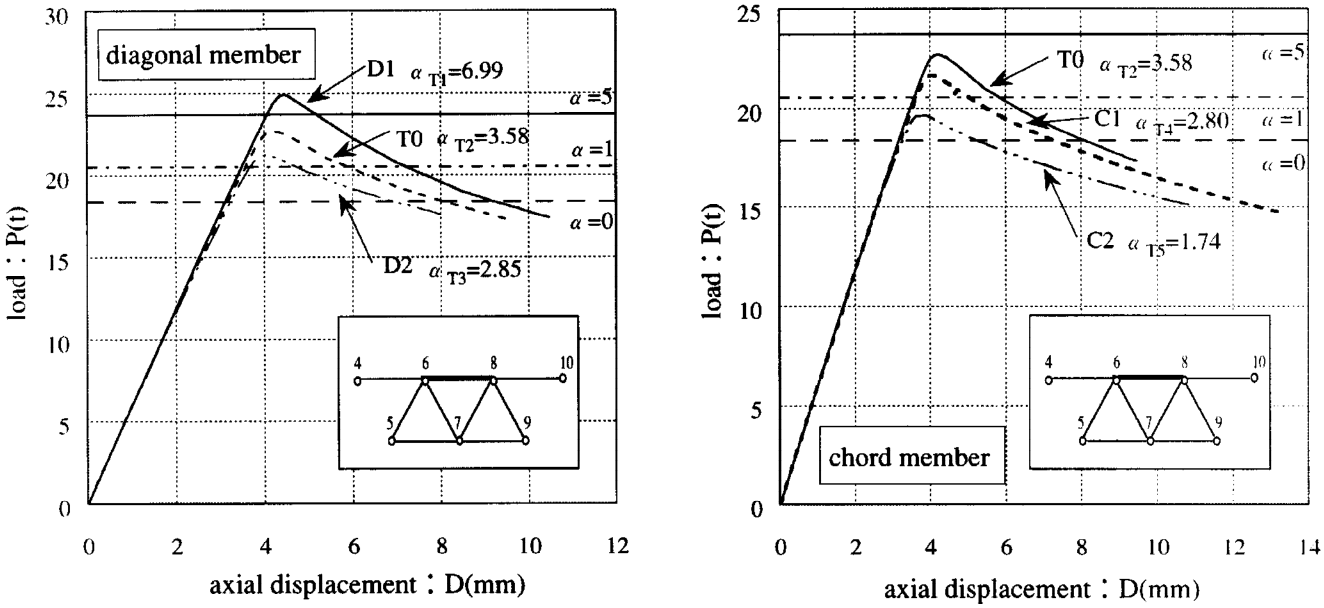

Fig.9. Load - axial displacement relation

EFFECT OF DIAGONAL MEMBERS

As the buckling member 6-8 receives the effect of elastic stiffness from the abutting members, the strength of this member increases and the effect of the diagonal member becomes greater with increasing flexural stiffness of the diagonal member. The diagonal 1 is the model in which the diagonal member has the same size as the chord member. In this model, the effect of the diagonal member is greater. Accordingly, the moment sharing ratio by the two diagonal members (5-6 and 6-7) at the node 6 is higher but the sharing ratio of the chord member is smaller. The diagonal 2 is the model in which the size of the diagonal member is still smaller than that in the truss 0. In this model, therefore, the effect of the diagonal member 5-6 receiving the compressive force is small and the chord member 4-6 bears more than 50 percent of the moment. In all models, the burden on the diagonal members, particularly the member 6-7 receiving the tensile force, decreases but the burden on the chord member 4-6 tends to increase after buckling. The axial force to be borne by the diagonal members in the truss when the load is concentrated at the central point (node 7) is smaller than the force to be borne by the chord members. Accordingly, the use of the diagonal members having a diameter equal to or larger than the chord members is not reasonable as an excessive effect is obtained.

EFFECT OF CHORD MEMBERS

If the flexural stiffness of the abutting members decreases, the effect of the chord member decreases and the buckling strength of the buckling member decreases. As the effect of the chord member in the chord 1 is smaller than that in the truss 0, the diagonal members, particularly the member 6-7 receiving the tensile force, bear more than 50 percent of the moment at the node 6. After buckling, the effect of the chord members shows a scant increase. In the chord 2, the buckling strength of the abutting chord member 4-6 is lower and is more likely to buckle compared with that in the chord 1. Under this condition, the chord member 4-6 does not show any effect on the buckling member 6-8 but, on the contrary, receives the effect from the abutting members and the effect of the diagonal members becomes greater. In the chord 2, therefore, the member 6-8 buckled earlier than the abutting members (4-6 and 8-10) which had been thought to buckle earlier. When the flexural stiffness of the abutting chord members decreases and their buckling strength is reduced to a critical level, the effect of these members on the buckling member decreases. If the flexural stiffness of the diagonal members is further decreased, the supporting condition approaches the condition in which the both ends are simply supported.

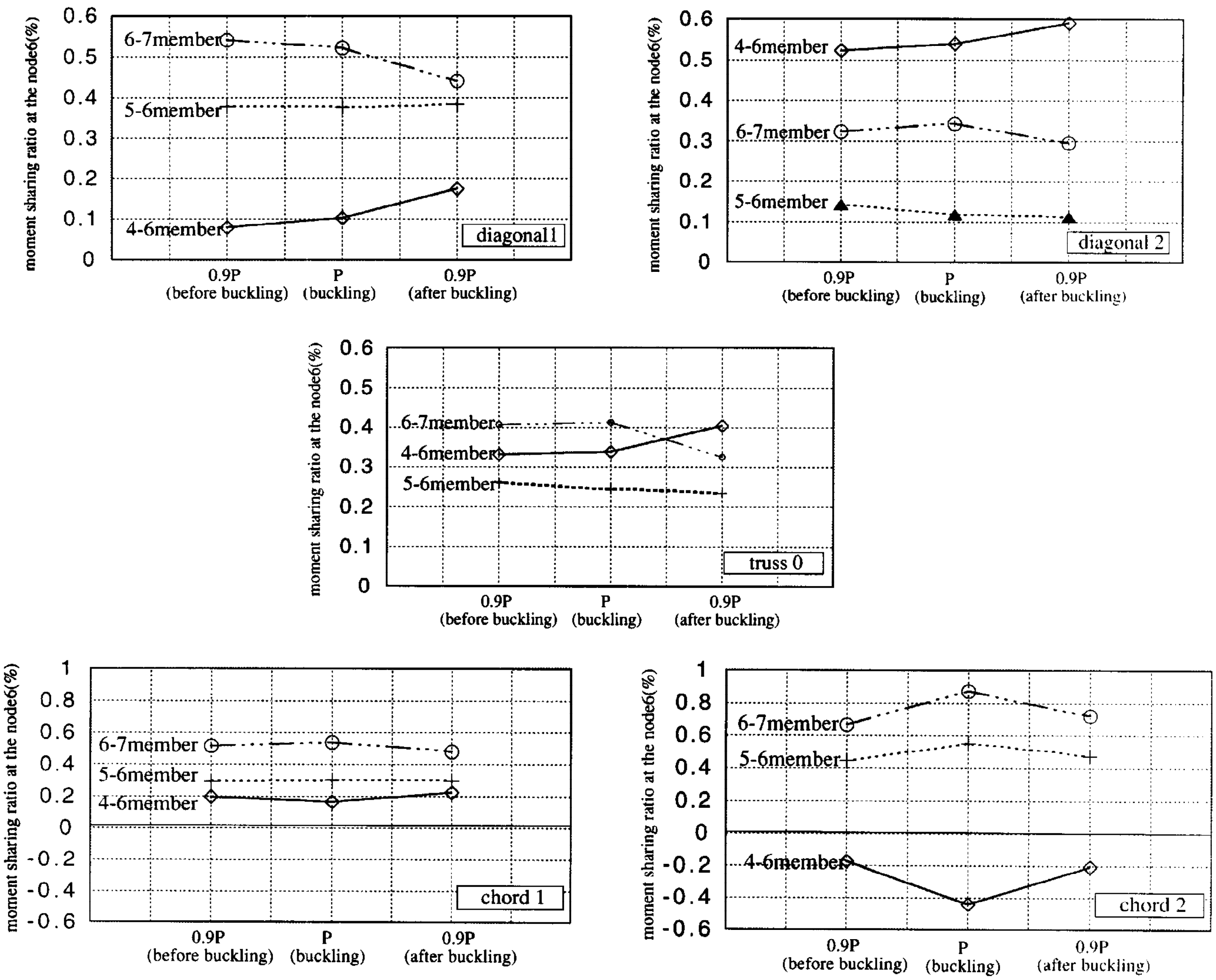

Fig.10. Moment sharing ratio at the node 6

CONCLUSION

To reproduce the effect of the abutting members on a given member in a truss structure, repeated loading test was conducted by installing rotation constraining mechanisms at both ends of the specimen. As a result, it was found that the effect of rotation constraint on buckling strength increases with increasing slenderness ratio of specimen.

When studying the behavior of the truss members in compression, the behavior of truss structure can be evaluated more accurately by grasping the effect from the abutting members rather than by handling the truss members in the condition where their both ends are simply supported, making it possible to design truss structures more rationally and economically.

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