WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA
Advancing Timber for the Future Built Environment

BUCKLING PERFORMANCE OF NAIL LAMINATED TIMBER FOR BEARING SHEAR WALL, BUCKLING TESTS AGAINST VERTICAL LOAD FOR LOAD-BEARING WALLS

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ABSTRACT: The goal of this study is to propose a design formula for the buckling load of NLT bearing walls. To this end, a buckling test method was examined that assumes out-of-plane buckling of NLT bearing walls, and the final test method was determined. A bending test was also conducted using a specimen with the same specifications as the buckling test. The stiffness EI was then calculated from the results of the buckling test and bending tests, and a comparison was made performed. It is believed that the buckling test with pins at both ends can be used to verify the difference between a pure buckling test and a bending test. In the future, based on a comparison of the stiffness EI from the buckling test and bending test, an adjustment coefficient (reduction coefficient) that converts the buckling test to a bending test will be proposed, leading to the proposal of a design formula.

KEYWORDS: Nail Laminated Timber, Buckling Tests, Bending Tests, Butt Joints, Stiffness EI

1 – INTRODUCTION

Nail Laminated Timber (NLT)is about to be introduced as an effective building component to promote the use of wood in Japan. NLT is a massive member made by nailing together structural lumber for 2x4 construction, and is sometimes used as horizontal members for floors and roofs in North America (Fig. 1). In North America, NLTs are used as horizontal members for floors and roofs. Compared to CLTs, which require glueing and compaction equipment, NLTs, which do not use glue, can be manufactured not only in the factory but also on site in some cases, thus reducing transportation route restrictions despite the huge panels.

In Japan, the use of NLT is not only limited to horizontal members, but is also being considered for use in vertical members, such as load-bearing walls (Fig. 2). Verification of horizontal forces, such as seismic force and wind pressure is currently being verified. However, load-bearing walls are also structural members that support vertical forces such as fixed loads and live loads in buildings. Therefore, it is also necessary to verify buckling and fracture properties caused by vertical loads. However, buckling tests are subject to sudden destruction and involve risks such as falling knife edges at the head of the column. Because of that, we attempted to reproduce or substitute bending tests for the buckling tests.

To put NLT load-bearing walls into practical use, we will conduct research with the ultimate goal of constructing an academic design formula for allowable buckling strength, which will serve as a design standard.

This paper reports on the progress of the buckling tests conducted so far and the comparison and verification of the stiffness EI obtained from the buckling tests and the stiffness EI obtained from the bending tests.

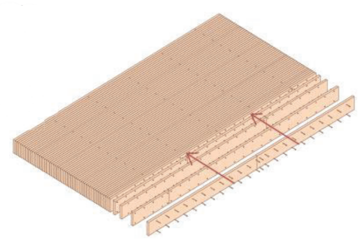

Fig.1 *NLT installation method*

Fig.2 *NLT load-bearing wall*

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https://doi.org/10.52202/080513-0542

2 – SUMMARY OF RESEARCH

To reproduce the out-of-plane buckling of NLT bearing walls, tests were conducted on a specimen from which a portion of the NLT bearing wall was extracted. As a result, issues such as control of the buckling direction and Compression Perpendicular to the grain in Wood emerged the wood were observed. Therefore, the shape of the specimen and the test method were improved, and the final test method was fixed.

Then, in order to suggest an adjustment factor (reduction factor) to replace the buckling test with the bending test, the stiffness EI calculated from the buckling test results was compared and verified with the stiffness EI calculated from the bending test results.

3 – BUCKLING TESTS

3.1 – CONSIDERATION OF SPECIMEN SHAPE

The specimen was a set of five lumbers, referring to the "overlap of butt joint (BJ) positions in the width direction of the floor and roof slab every five layers" described in the NLT construction manual. First, to reproduce the actual structure of an NLT load-bearing wall, the test specimen was made by extracting from the beam to the foundation (Fig. 3). However, with this specimen shape, damage occurred to the beams in the out-of-plane direction, making it impossible to perform a buckling test (Fig. 4). Therefore, the beam and foundation were removed, and the specimen was changed to an extracted form from the double top plate to the bottom plate. The nail pitch between the lumber pieces was CN75@200 staggered, the same as that of the preceding wall specimen[1)]. As a result, because the length of the double top plate and the bottom plate was only 300 mm, occurs a fiber orthogonal compression perpendicular to the grain into the double top and bottom plates, causing cracks at the ends of the materials (Fig. 5). In addition, the test specimen buckled in the in-plane direction as an NLT bearing wall. Therefore, two improvements were made to the test specimen. The length of the double top and bottom plates was changed to 500 mm to prevent cracking (Fig. 3). Since it was unlikely that the test specimen would buckle in-plane as a load-bearing wall, the number of nails was doubled to @100 staggered to improve the degree of fixation between the lumber members so that the test specimen would buckle out-of-plane. Additionally, assuming that when NLT load-bearing walls are put to practical use, surface materials will be used as a finishing touch, tests were also conducted with the specimen covered in plasterboard on both sides (Fig. 2). As a result, it was confirmed that the specimen underwent out-of-plane buckling by increasing the number of nails to improve the unity of the lumber or by covering the sides with plasterboard (Fig. 11). After the above pre-tests, tests were conducted using the five specifications (Table1, Fig.6~10). The results showed that in-plane buckling occurred in some test specimens even when the nail pitch was @100 and two lines were driven.

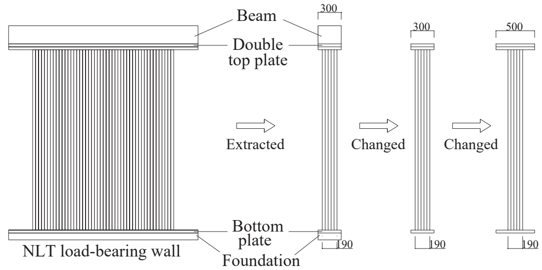

Fig.3 *Consideration of specimen shape*

Fig.4 *Beam Damage*

Fig.5 *The edge of the material is cracked*

Table 1 *Specimen specifications*

Specimen name	Nail pitch	Number of butt joints	Plasterboard
Type 1	@100 two lines	1	×
Type 2	@100 two lines	0	×
Type 3	@100 two lines	3	×
Type 4	@100 two lines	1	○
Type 5	@200 two lines	1	○

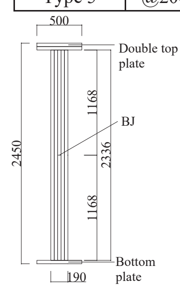

Fig. 6 *Type 1 test specimen*

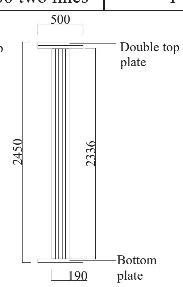

Fig. 7 *Type 2 test specimen*

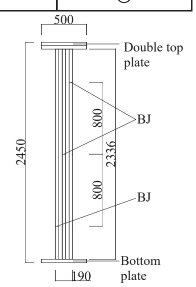

Fig. 8 *Type 3 test specimen*

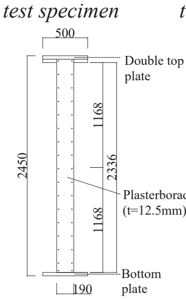

Fig. 9 *Type 4 test specimen*

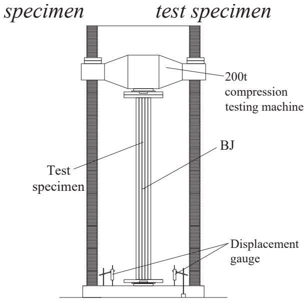

Fig. 10 *Specimen installation state*

Fig. 11 *Out-of-plane buckling of plasterboard-covered specimens*

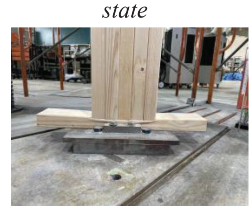

Fig. 12 *Compression of the frame materials*

https://doi.org/10.52202/080513-0542

3.2 – IMPROVEMENT OF TEST METHOD AND BUCKLING LENGTH

The buckling tests conducted so far have been carried out using a test method that has a buckling length of 0.9ℓ based on previous research. However, in-plane buckling occurred was observed in some of the test specimens. In addition, the elastic range could not be accurately determined because of a fiber orthogonal compression perpendicular to the grain into the double top and bottom plates (Fig. 12). Therefore, we improved the test method to control buckling in the out-of-plane direction and eliminate any compression of the frame materials.

First, to eliminate any compression of the frame materials, we conducted tests without frame materials on the vertical frame alone (with both ends directly attached to the jig). As a result, we were able to eliminate the effects of compression perpendicular to the grain in the wood, but the test specimen buckled in the in-plane direction. Therefore, for subsequent test specimens, we decided to change the shape of the test specimen to a single vertical frame alone.

Next, it was decided to use a knife-edge jig was used to control the buckling direction. Considering test safety, a knife edge was used only on the lower jig, and the test method was changed to a buckling length of 0.7ℓ for the rigid connection on one side (column head) and the pin on the other side (column base). On the column head side, the test specimen for the NLT parts alone was directly attached to the steel frame jig that had been used in previous tests, eliminating compression perpendicular to the frame and equivalent to a rigid connection with no rotation angle(Fig. 13). Similarly, the test specimen at the base of the column was directly attached to the knife edge, with a pin specification that did not restrict the rotation angle (Fig. 14). The load-displacement curve is shown in Figure 15, and the test results are shown in Table 2. Because the tests were conducted using a knife edge as the jig for the base of the column, it was thought that the buckling direction could be reliably controlled in the out-of-plane direction even with the standard specification in the NLT construction manual of 200 nail pitch in two lines, but the result was in-plane buckling (Fig. 16). Therefore, tests were also conducted with specifications that doubled the number of nails. With this specification, in-plane buckling occurred using the test method previously reported[2)] (buckling length 0.9ℓ), but as a result of using knife edges at the base of the columns, the test specimen buckled in the out-of-plane direction (Fig. 17). Simply changing to a knife edge at only the base of the column was not enough to control the buckling direction of the test specimen, which was two lines of nails 200, in the out-of-plane direction, as this is the standard specification. Therefore, it was decided to also change the jig on the column head side to a knife edge. However, there is a risk that a knife edge at the column head will cause the jig to fall due to the sudden destruction of the test specimen. For this reason, a jig was designed that would not fall and restrict rotation angle even if the test specimen was subject to sudden destruction. Because there was a risk that the convex jig, which was attached directly to the test specimen, would fall, we also designed a fall-prevention jig (a rectangular plate jig) to connect to the concave jig fixed to the upper crosshead. The fall prevention jig uses an M12 bolt to connect the convex jig and concave jig. In addition, the hole through which the bolt passes is a long hole and is designed not to restrict the rotation angle when the test specimen buckles and the fall prevention jig is hooked on the bolt to prevent the knife edge from falling (Fig. 18,19).

Fig.13 *the steel frame jig*

Fig.14 *knife edge Jig*

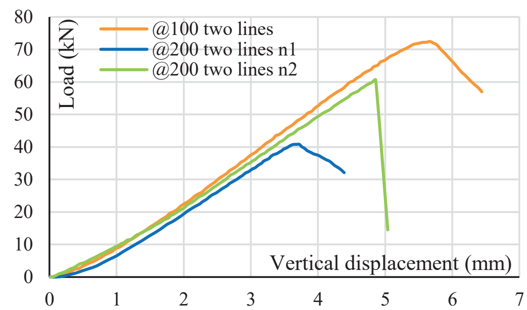

Fig. 15 *Load – displacement*

Table 2 *Test results (Pins on both ends)*

	K	Pmax	2/3 Pmax	Pa	buckling direction
unit	kN/mm	kN	kN	kN	-
@100 two lines	47.32	289.76	193.17	193.17	Out-of plane
@200 two lines n1	37.00	163.28	108.85	108.85	In-of-plane
@200 two lines n2	44.00	242.40	161.60	161.60	In-of plane

Fig.16 *In-of-plane buckling*

Fig.17 *Out-of-plane buckling*

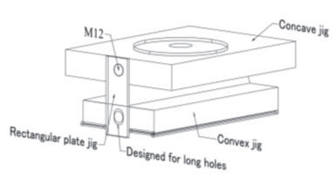

Fig.18 *Knife edge drawing*

Fig.19 *Column head knife edge*

https://doi.org/10.52202/080513-0542

4 – SUMMARY OF EXPERIMENTS

Knife edges were used at both the column head and base, and the tests were conducted with a pin buckling length of 1.0ℓ at both ends. A 200t compression testing machine manufactured by Nippon Institute of Technology was used for the test (Fig. 20). The loading rate was approximately 0.2 kN/s, and after measuring the maximum load, the load was applied until the test piece suffered buckling failure or the load decreased to 80% of the maximum load.

5 – SPECIMEN SPECIFICATIONS

The test specimens were of two specifications: 100 two-line construction, the same specifications as in previous tests, and 200 two-line construction, which is the standard specification in the NLT construction manual (Fig. 21). The test specimens were designed without BJs. A total of six specimens were tested, three of each of the two specifications.

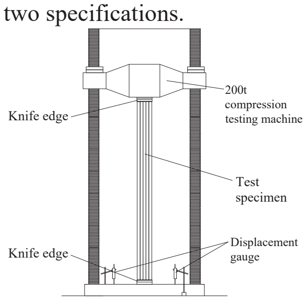

Fig. 20 *Specimen installation state*

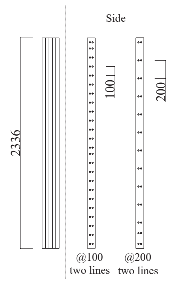

Fig. 21 *Specimen*

6 – EXPERIMENTAL RESULTS

The load-displacement curve is shown in Figure 24, and the test results are shown in Table 3. By using knife edges at both the column head and base, the buckling direction was able to be controlled to the out-of-plane direction even with a nail pitch of 200 mm (Fig. 22,23). When comparing Pmax, no significant difference was seen whether the nail pitch was 100 mm or 200 mm, and it is thought that the degree of nail fixation has little effect on the maximum load when the test specimen buckles out-of-plane. In addition, a comparison was made for Pmax based on the difference in buckling length (Table 4). Because the buckling length changed from 0.7ℓ to 1.0ℓ, it is thought that the theoretical value for Pmax for a buckling length of 1.0ℓ is 0.49 times lower than that for a buckling length of 0.7ℓ. When comparing based on the average test results, the theoretical value and experimental value were almost identical, with Pmax for the 100 specification being 0.51 times that of a buckling length of 0.7ℓ. However, when comparing the experimental value for the 200 specification, it was 0.75 times, which is larger than the theoretical value. This is thought to be due to the fact that with a buckling length of 0.7ℓ, the test specimen experienced in-plane buckling, and with a buckling length of 1.0ℓ, out-of-plane buckling occurred, resulting in a difference in the buckling direction.

Fig.22 *Out-plane buckling (@100)*

Fig.23 *Out-plane buckling (@200)*

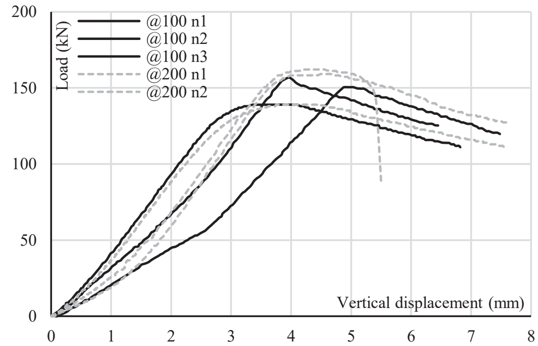

Fig. 24 *Load – displacement (Pins on both ends)*

Table 3 *Test results*

	K	Pmax	2/3 Pmax	Pa	buckling direction
unit	kN/mm	kN	kN	kN	-
@100 n1	43.06	139.02	92.68	92.68	Out-of plane
@100 n2	22.46	150.54	100.36	100.36	Out-of plane
@100 n3	33.19	156.86	104.57	104.57	Out-of plane
@200 n1	40.22	139.04	92.69	92.69	Out-of plane
@200 n2	30.56	159.20	106.13	106.13	Out-of plane
@200 n3	33.53	162.14	108.09	108.09	Out-of plane

Table 4 *Comparison of theoretical and experimental values*

Theoretical value: Pk	$P_k=1/(0.7\ell)^2$	$\times 0.49 \rightarrow$	$P_k=1/(1.0\ell)^2$
Experimental value: Pmax (@100 two lines)	289.76kN	$\times 0.51 \rightarrow$	148.80kN
Experimental value: Pmax (@200 two lines)	202.84kN	$\times 0.75 \rightarrow$	153.46kN

Fig.25 *Compression side damage*

Fig.26 *Knife edge during testing*

7 – BENDING TESTS

7.1 – SUMMARY OF EXPERIMENTS

To ensure consistency with the buckling tests, the test specimens used were of the same specifications as those used in the buckling tests. A 200t universal testing machine was used for the tests, and a four-point bending test was performed to avoid direct force application to the central BJ and to reproduce the buckling length in the buckling test (Fig. 27). In order to reproduce out-of-plane buckling, a force was applied in the out-of-plane direction of the test specimen. The loading rate was approximately 0.2 kN/s, and after measuring Pmax, the load was applied until the load decreased to 80% of Pmax.

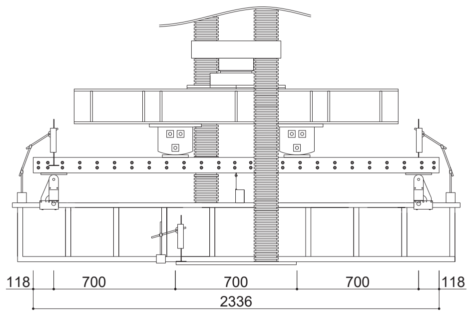

Fig. 27 *Specimen installation state*

7.2 – EXPERIMENTAL RESULT

The load-displacement curve is shown in Figure 30~35, and the test results are shown in Table 5. Comparing the initial stiffness, the largest values were observed for BJ0, 1, and 3 in that order. The specimens were divided into two groups based on whether or not there was a central BJ, and within each group, specimens with fewer BJs tended to have higher initial stiffness. The same tendency was observed for the maximum load, but the opposite phenomenon was observed for BJ1 and BJ5. The reason for this is that the specimens with BJ1 had a lot of damage at the knots. This caused the lumber to split at the knots, which was thought to have prevented the load from increasing (Fig. 28,29).

Table 5 *Test results*

	Pmax	δPmax	K	Py	δPy
unit	kN	mm	kN/mm	kN	mm
BJ0	32.68	55.81	0.72	21.30	29.23
BJ1	23.16	44.12	0.62	13.43	21.35
BJ2	31.09	48.51	0.70	19.38	24.22
BJ3	25.13	48.79	0.61	14.91	23.67
BJ4	26.77	51.08	0.62	15.63	25.07
BJ5	26.81	54.52	0.61	17.70	28.59

Fig. 28 *Damage at the knots*

Fig. 29 *Lumber splitting*

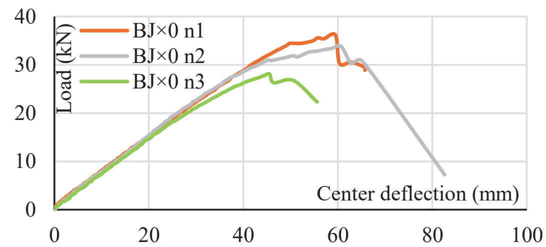

Fig. 30 *Load – displacement (BJ0)*

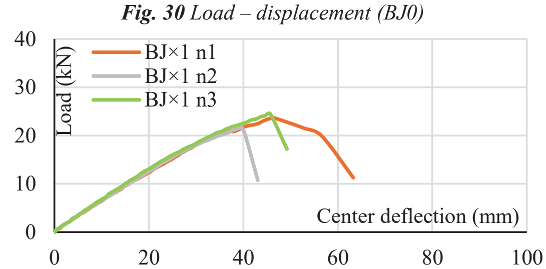

Fig. 31 *Load – displacement (BJ1)*

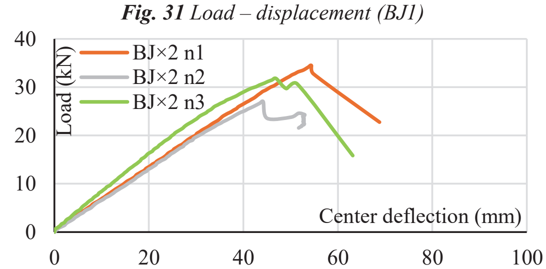

Fig. 32 *Load – displacement (BJ2)*

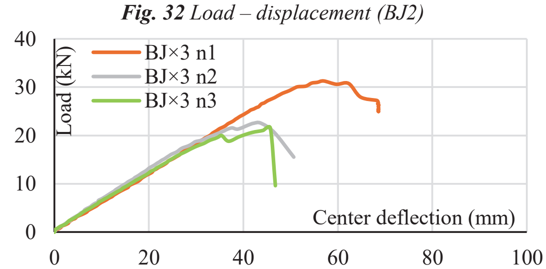

Fig. 33 *Load – displacement (BJ3)*

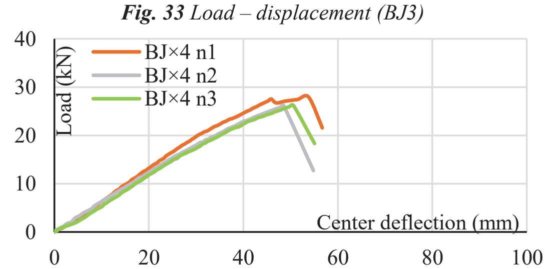

Fig. 34 *Load – displacement (BJ4)*

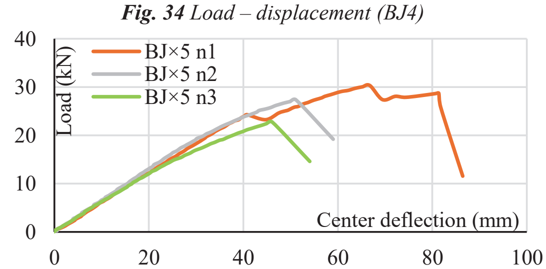

Fig. 35 *Load – displacement (BJ5)*

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8 – COMPARISON OF STIFFNESS EI BETWEEN BUCKLING TESTS AND BENDING TESTS

The EI values from the buckling test and the EI from the bending tests were calculated based on the test results and compared (Fig. 36,37). The EI values obtained from the buckling test with pins at both ends (ℓk=1.0ℓ) and the bending test are shown in Table 6. The EI values from the buckling test were 0.1, 0.4, and 0.9 Pmax was almost linear, Py could not be calculated, so EI was calculated from Pmax. The EI from the bending test was calculated based on Py. When comparing the EI from the buckling test with the EI from the bending test, the EI from the bending test was 1.52 times higher than the EI from the buckling test.

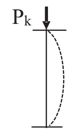
A previous report also compared the EI from buckling tests with different buckling lengths and the EI from bending tests, showing that when both ends were fixed (ℓk=0.9ℓ), the EI from the bending test was approximately 1.8 times higher(Table 7), and similarly, when one side (head side) was fixed and one side (base side) pinned (ℓk=0.7ℓ), the EI from the bending test was approximately 1.5 times higher(Table 8). In the buckling tests compared in the previous report, it is thought that noise such as the effects of compression perpendicular to the grain in the wood and variation in buckling length depending on the test specimen influenced the difference in EI between the buckling test and the bending test.

On the other hand, in the buckling tests with pins at both ends conducted this time, the NLT parts were used as a test specimen alone, eliminating compression perpendicular to the grain in the wood, and by using knife edges on both ends, it was possible to suppress variation in buckling length and make it possible to purely compare the EI from the buckling test and the bending test. In the future, it will be necessary to verify the adjustment coefficient (reduction coefficient, etc.) when converting the buckling test to a bending test based on the difference between the EI from the buckling test and the EI from the bending test. For this reason, it is thought that verification with further parameters and more test specimens is necessary.

9 – CONCLUSIONS

We investigated a buckling test method that assumes that NLT bearing walls buckle in the out-of-plane direction.

In order to eliminate the problem of eliminating the effect of a fiber orthogonal compression perpendicular to the grain into the double top and bottom plates, which had been an issue in previous tests, and to control the buckling direction, we conducted tests with a buckling length of 1.0 ℓ using knife edges at the head and base of the column. By conducting tests with pins at both ends, we confirmed that buckling in the out-of-plane direction occurs even with a nail pitch of 200, two lines, which is the standard specification in the NLT construction manual. In addition, when comparing the stiffness EI from the buckling test and the stiffness EI from the bending test, the stiffness EI from the buckling test with pins at both ends and the stiffness EI from the bending test showed the closest values. Since the difference between the stiffness EI from the buckling test and the stiffness EI from the bending test is considered to be the difference between pure buckling and bending, it is thought that an adjustment coefficient can be calculated based on this value when converting the buckling test to a bending test. In order to calculate the adjustment coefficient, it is thought that further parameters and the number of test specimens will be increased and statistical verification will be necessary.



$$P_k = \frac{\pi^2 EI}{{l_k}^2}$$

Fig. 36 Calculation formula for stiffness EI from buckling test

$$\delta_c = \frac{23Pl^3}{648EI}$$

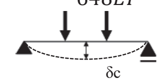


Fig. 37 Calculation formula for stiffness EI from bending test

Table 6 Comparison of stiffness EI(ℓk=1.0ℓ)

	Buckling		bending		
	Pmax	EI	Py	δ(Py)	EI
BJ0	148.80	82.27	21.30	29.23	119.76

Table 7 Comparison of stiffness EI(ℓk=0.9ℓ)

	Buckling		bending		
	Pmax	EI	Py	δ(Py)	EI
BJ1	126.20	56.51	13.43	21.35	103.38
	Pmax	EI	Py	δ(Py)	EI
BJ3	124.70	55.84	14.91	23.67	103.52

Table 8 Comparison of stiffness EI(ℓk=0.7ℓ)

	Buckling		bending		
	Pmax	EI	Py	δ(Py)	EI
BJ0	289.76	78.50	21.30	29.23	119.76

ACKNOWLEGEMENT

This research was supported by Grant-in-Aid for Scientific Research (C) No. 24K07755 for FY2024-2026.

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