A STUDY ON VARIABLE STIFFNESS DEVICE HAVING ELASTIC NON-LINEAR CHARACTERISTICS

Hideo SUITSU[1]

SUMMARY

This variable stiffness device has unique characteristics in the restoring force. The elastic non-linear characteristics is provided by prestressed joints with prestressing steel rods. Installation of this device enables the stiffness of building to remain rigid during strong typhoons or medium earthquakes and to reduce during more strong earthquakes so that the response force is decreased. After such a strong earthquake, the stiffness changes back to the high rigidity with the elastic restoring force. This paper reports the results of static experiments on this device and dynamic analysis of its efficiency during strong earthquakes.

INTRODUCTION

The characteristic curve of this variable stiffness device is non-linear and restoration is achieved elastically. By this mechanism, a comparatively higher stiffness is kept during typhoons or medium earthquakes, while the response force is reduced during strong earthquakes because of the building stiffness to be flexible. This variable stiffness device is composed of prestressing steel rods and relatively rigid compressive materials (concrete, steel, etc.). A simplest example is shown in Fig.1, in which two steel boxes are tightly prestressed with a prestressing steel rod. When this combined member is pulled at the both ends in parallel to the member axis, the initial stiffness is the sum of those of the prestressintg steel rod and box components. But, when the pulling force exceeds the initial prestress force, the metal-touched parts of box components separate to retain the stiffness of prestressing steel rod only to be effective. However, the pulling force is reduced to the original value, the load-deformation relation will return to the original point passing through the same path without any residual deformation(Fig.2).

This paper reports the results of the static experiments on this variable stiffness device in a bearing wall of which shear stiffness is elastic non-linear type. And the dynamic analysis of the 1 mass-model having this device is discussed as well.

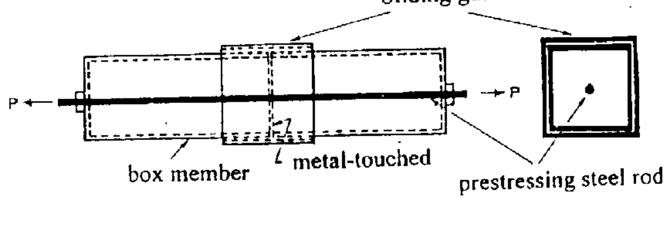


Fig.1 Example of variable stiffness device

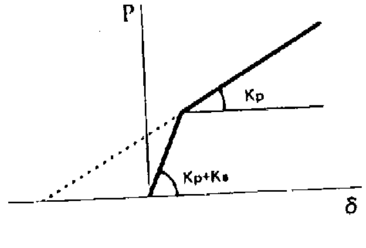


Fig.2 Load-deformation curve of variable stiffness device

[1] *Senior Engineer , Nikken Sekkei, Tokyo, Japan Email: suitsu@nikken.co.jp*

Several solutions are possible for application of this device, among which some representative methods are briefly explained. Table 1 shows examples for the use of this device in bearing walls and coupling beams which have more effect on the building stiffness.

In all of cases, the devices are composed of combination of prestressing steel rods and rigid compressive components. Use of this device depends on the system of framework, condition of external forces, stress distribution, etc., and they are to be chosen adequately according to these factors.

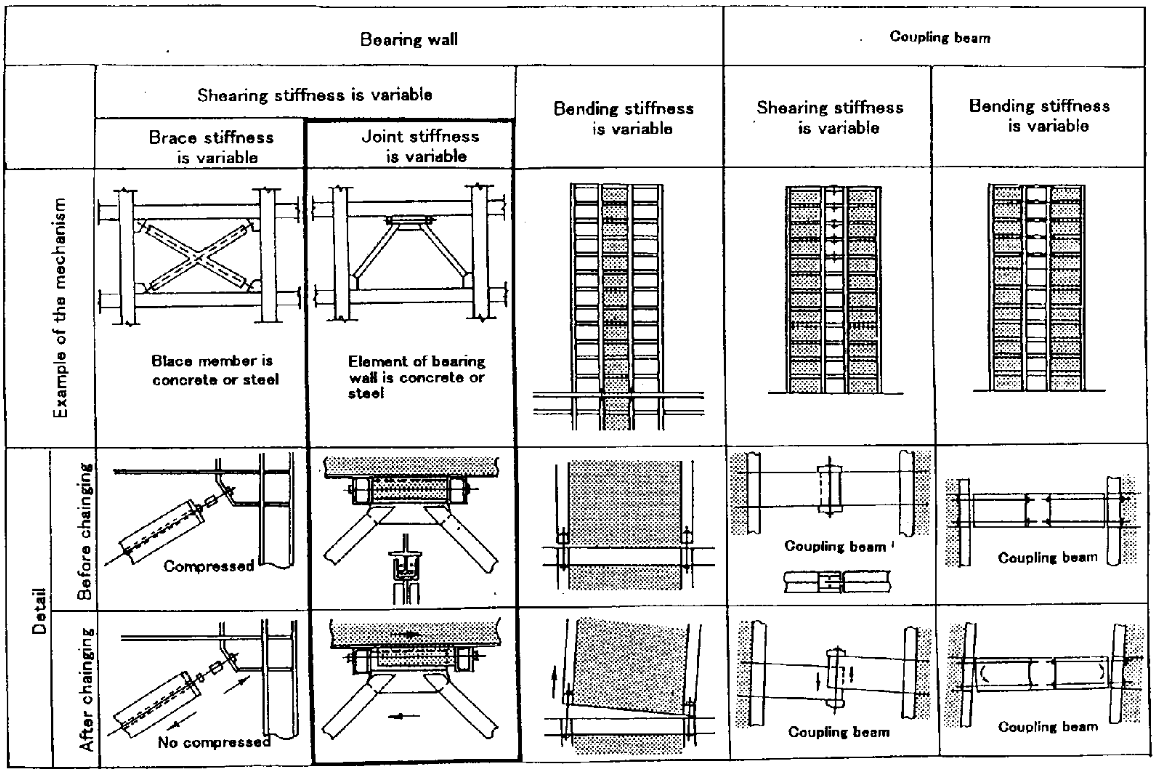
STATIC EXPERIMENTS ON THE VARIABLE STIFFNESS DEVICE

A static force was applied on a bearing wall of which shearing stiffness is variable by the prestressed metal-touched joints of braces, to confirm experimentally the behavior of the device in the stiffness, stiffness changing point and deformation ability**.**

Test Specimen

As shown in Fig.3, positive and negative loads are applied on the center of the specimen with K type steel braces. The joint of brace to frame-beam is provided with a variable stiffness device which is tightly metal-touched by prestressing steel rods in the parallel direction of the beam axis. In this experiment, the initial prestress force is 60 tons with four prestressing steel rods. The ratio of the stiffness of the braces to frames is calculated as 1 : 0.225 before the stiffness change. When the applied load is 60x1.225=73.5 tons, the metal-touched part will separate and the stiffness will reduce.
The yield strength of a prestressing steel rod is 27.3 tons (109 tons with four), that is the elastic range of the joint is 109 tons. Hence the ratio of the stiffness of brace to frame is calculated as 1 : 1.05 after the stiffness change. Therefore, the maximum load within the elastic range is 73.5 + (109-60)x(1.0+1.05)=174 tons.

Table 1 Variable stiffness device in bearing wall and coupling beam



As mentioned before, the main element composing the variable stiffness device is a prestressing steel rod which supplies the initial prestress. Tensile test was executed for the prestressing steel rods including the metal-touched parts with the spherical nuts and washers to confirm the overall elongation behavior. In the test, because of the deformation at the spherical nuts and washers, the apparent Young' modulus was $1.74x10^6 kg/cm^2$. This value is

80% of the Young' modulus of the prestressing steel rods, 2.18×10^6 kg/cm^2. In the result of this test, it is mentioned that the Young' modulus is lower for the shorter rods with fixing parts because of the deformation at the metal-touched part. The percentage of total elongation at rupture of the prestressing steel rod with the fixing parts is influenced by the length, because the whole length dose not elongate uniformly, and local elongation occurs at the rupture. At this test, the elongation percentage was 2.3% in the gauge length of 1000mm. According to JIS for the method of tensile test of metallic materials, the gauge length shall be 8 times of the rod's diameter, that is 144mm for a diameter of 18mm,and elongation percentage shall be 5% or more.
The specimen material specification is as follows:

- Steel : SM 50A
- Prestressing steel rod : class 4 (nominal diameter 18mm)

Loading Arrangement And Measurement

Positive and negative loads, P and –P, were applied on the specimen as shown in Fig.3. Displacement and strain were measured by dial gauges and wire strain gauges respectively. In the elastic range of the prestressing steel rods, the behavior of the variable stiffness device, namely elastic non-linear characteristic was confirmed. Increasing the load further, behavior of the specimen was examined in the plastic range and the rupture stage of the prestressing steel rods.

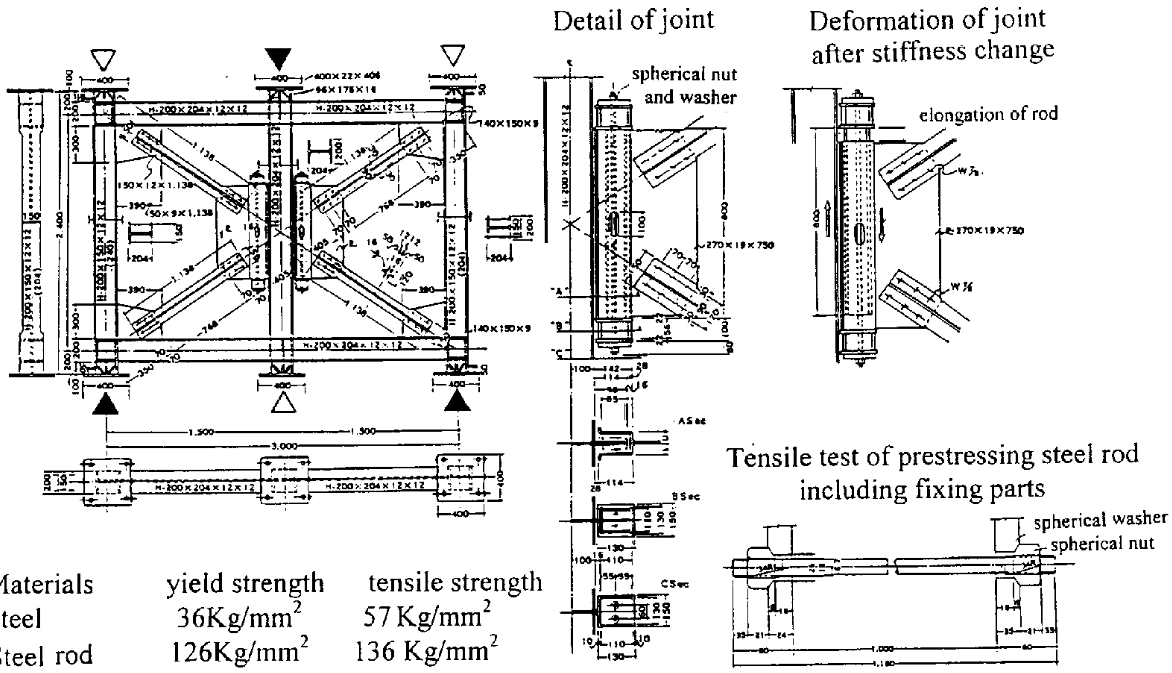


Fig. 3 Specimen and its details

EXPERIMENTAL RESULTS

Strain of the PC steel rods

As shown in Fig.4, the strain of the prestressing steel rods remarkably increased at a load of near 75t, which means that the rigid connection changed to be flexible due to release of the initial prestress. After the stiffness change, the loads was increased up to 180t, then decreased to the origin. The stress-strain relation returned to the original point following the path same to the increasing path, showing a elastic non-linear behavior. The load was increased again up to 230t over the elastic range (190t) of the prestressing steel rods, then decreased to the origin. The stress-strain relation returned back on parallel with the second stiffness with a relatively small residual strain. The circle marks (o) in Fig.4 show the calculated values.

Load –deflection curve

Fig. 5 shows the load-deflection curve of the specimen. At a load of 70t, the stiffness changed to be small (about 35 % of the initial stiffness). After the stiffness change, the load was increased up to 180t, then decreased. The load-deflection relation returned elastically back to the original point following the path nearly same to the increasing path. At a load of 80t, the stiffness changed back to the initial rigidity, because the metal-touch occurred again at the fixing part. At the original load (0 ton), the residual deflection was 0.5 mm . With this hysteresis curve, it was confirmed that the device is elastic showing the non-linear behavior before the load reaches where the deflection is 6.25mm At a load of 190t, the second reduction of stiffness occurred owing to the yield of the prestressing steel rods. The third stiffness was about 40 % of the second stiffness. After the second change of the stiffness, the load was increased up to 230t, then decreased. The load-deflection relation returned back on parallel with the second stiffness path between the first and second stiffness changing points. The yielded prestressing steel rods were unable to press the metal-touched part any more and residual deflection was 2.5mm. The circle marks (o) in Fig.5 show the calculated values.

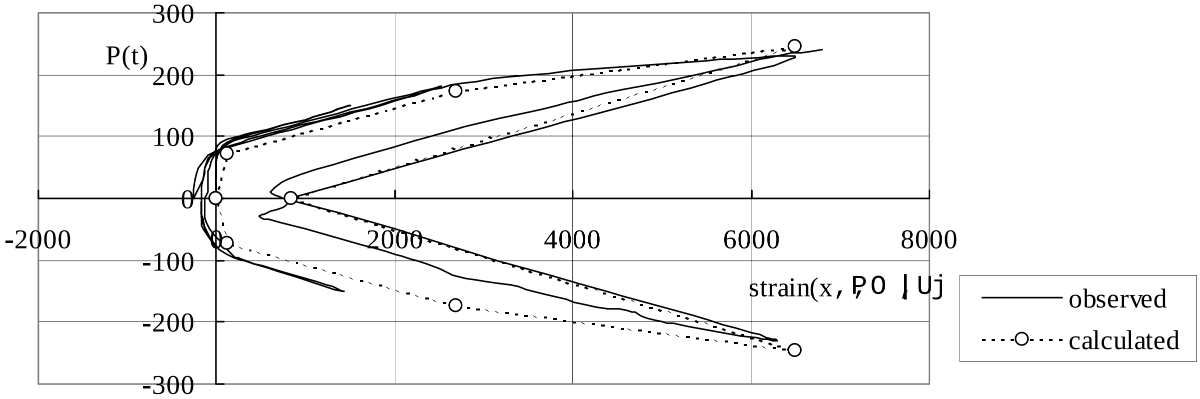


Fig.4 Load-Strain curve of rod

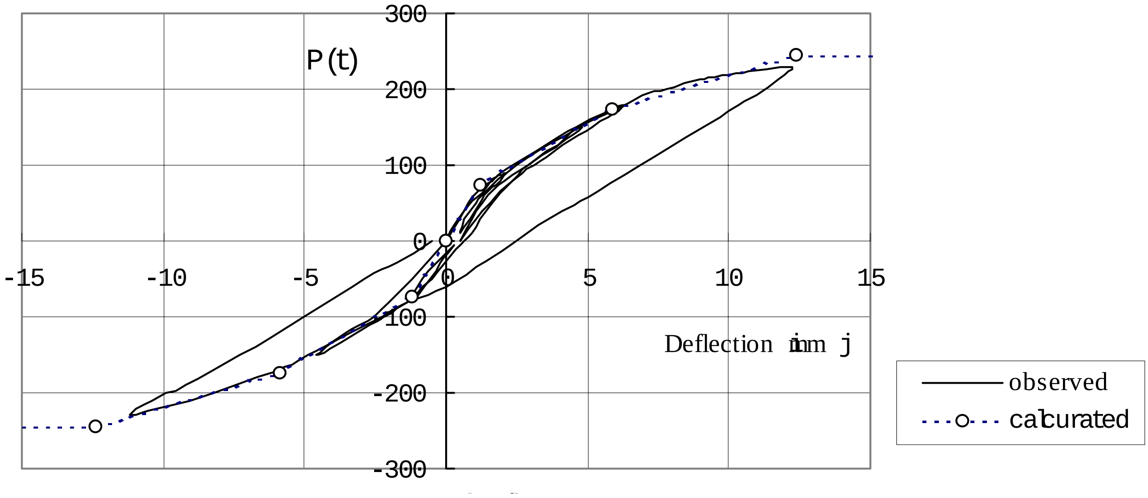


Fig.5 Load-Deflection Curve

Comparison with calculation

Fig. 6 shows an envelope curve of the observed hysteresis loops and calculated values for positive loading from the original point to the rupture of prestressing steel rods. The first change of the stiffness was caused by the separation of the metal-touched part at a load of 70t. The second change was caused by the yield of prestressing steel rods at a load of 190t. The third change was caused by the yield of the frame at a load of 240t. The rupture

of prestressing steel rods occurred at a load of 262t where the deflection was 22.3mm(1/67 of the story height). The circle marks(o) are the calculated values which are nearly equal to the measured values. In order to calculate the deflection of each step, the elongation of the prestressing steel rods was estimated taking account of the apparent Young's modulus and the local elongation at the rupture mentioned in 2.1 TEST SPECIMEN.
In Table 2, the values of the test result and calculation are shown for the stiffness, load and deflection at each step. The observed values are almost equal to calculated ones except the stiffness at the third and fourth steps. It is considered that the difference at those steps is caused by assuming a bi-linear(0 t/cm stiffness after yield) relation in the calculation for the frame stiffness.

Table 2 Test result and calculation

Step		Stiffness	Stiffness changing point Load(t)	deflection(mm)	situation
1st step	observed	K=560t/cm	70.0	1.25	From origin to separation of metal-touch
	caluculated	K_B=488	60.0	1.23	
		K_F=110	13.5	1.23	
		f ≒598	73.5	1.23	
2nd step	observed	K=209t/cm	190	7.0	From separation to yield of prestressing steel rod
	caluculated	K_B=105	109	5.9	
		K_F=110	65	5.9	
		f ≒215	174	5.9	
3rd step	observed	K=86t/cm	240	12.8	From yield of steel rod to yield of frame
	caluculated	K_B= 0	109	12.4	
		K_F=110	136	12.4	
		f ≒110	245	12.4	
4th step	observed	K=23t/cm	262	22.3	From yield of frame to rupture of steel rod
	caluculated	K_B= 0	109	21.8	
		K_F= 0	136	21.8	
		f ≒ 0	245	21.8	

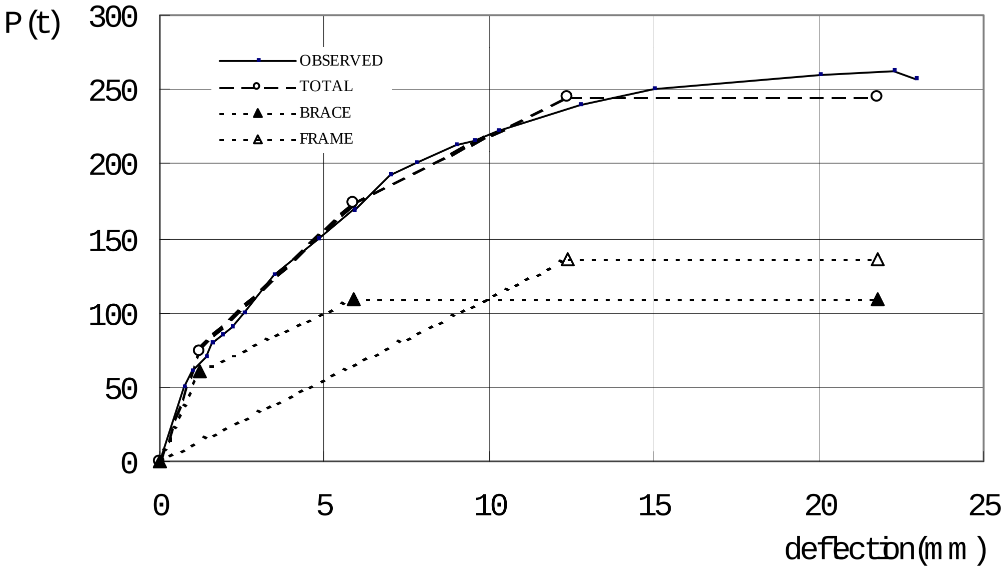


Fig.6 Load-deflection skeleton curve

DYNAMIC ANALYSIS FOR 1-MASS MODEL

For comparative study on the response behavior of the 1-mass model having different types of restoring force characteristics, the time history response analyses were carried out.
The three types of characteristics were linear type, variable stiffness type and loop type. The natural period of 1- mass model was varied from 0.2sec to 5.0sec.

The earthquake waves applied were considered those of EL Centro 1940 NS with maximum velocity of 50 kine(518 gal).
The stiffness changing point was set to be equal to the maximum value of the response shear force during the same earthquake with maximum velocity of 25 kine(259 gal) ,the second stiffness was to be 30% of the initial stiffness and 0.02 was applied for the damping coefficient h. Figure 7 shows the response shear force and displacement.

Response shear force coefficient:

The maximum values of the response shear force in the variable stiffness type are 30% to 35% less than those of the linear type in the case when the period is between 1.0 sec to 5.0 sec, and slightly larger than those of the loop type.

Response displacement:

The maximum values of the response displacement in the variable stiffness type are almost equal with those of the linear type except in the case when the period is less than 0.8 sec, and at 1.6 sec, 2.4 sec, 2.6 sec and 4.6 sec. The values of the loop type are almost 20% less than the linear type at all periods.

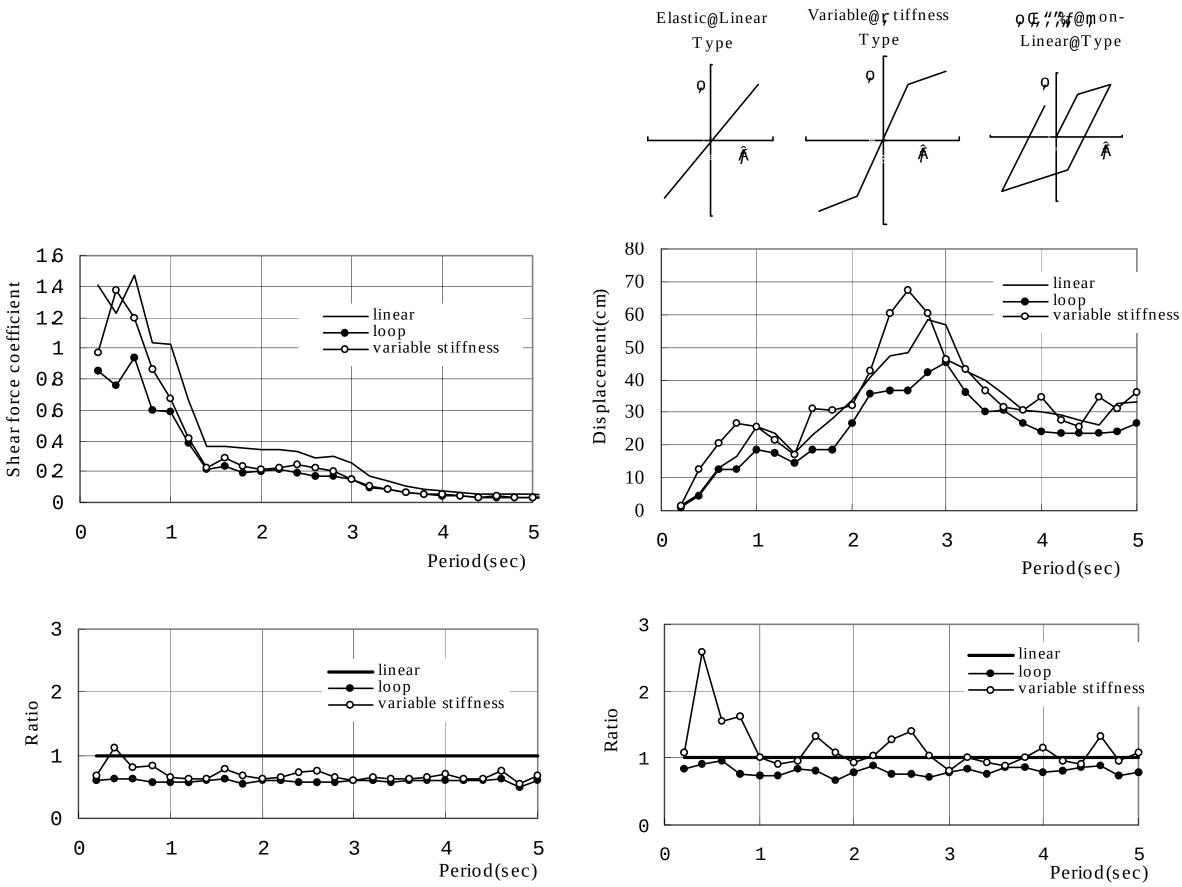


Fig. 7 Response shear coefficient and displacement

CONCLUSIONS

1.The variable stiffness device shows elastic non-linear behavior in the elastic range of prestressing steel rods which give the prestressing force at the metal-touched part of the joint.

2.The response shear force of 1-mass model having the variable stiffness device is 30 to 35% less than this of the linear type and slightly much than plastic non-linear type during strong earthquake with maximum velocity of 50 kine. The response displacement is almost equal or slightly much than linear type.

3.On evaluating the stiffness of prestressing steel rod, the deformation at the spherical nuts and washers shall be taken in to consideration. And the percentage of the total elongation at the rupture is influenced by the rod length because of the local rupture elongation.

REFERRENCES

1. Fukuzou Suto, Hideo Suitsu and others: The study of a high-raised building structure using bearing walls (2), Kentiku Gijutu, No 203 July, 1968.
2. Hideo Suitsu: Prestressed concrete for new aseismic element, Journal of Prestressed concrete, Vol.16, No.3, May,1974.