Development of Base Isolation System with Multi-Rubber Bearings and Improved Friction Dampers

Toshihiro KOIDE, Mototaka MATSUNO, Kouichirou KIMOTO, Yoshio ITOH
Technical Research Institute of Hazama Corp., Nishiyono, Japan

1 INTRODUCTION

Although the friction damper performs well dissipating hysteresis energy, but due to its characteristics of suddenly acting on and changing the direction in which the friction force operates, the theoretical infinite stiffness retards its filtering function of cutting high frequencies. And for small or moderate earthquakes it doesn't respond because of the lower shear force than the triggering friction force set for the friction damper.

Hence, previous "Friction Damper" which we had developed for a Base Isolation System was improved by connecting a "High-Damping Type Multi-Rubber" to it in series. The advantages of this improvement are to obtain the specified reasonable equivalent initial stiffness expected to cut high frequencies as a filter for from weak to strong ground motions, and to add a function of consuming hysteresis energy even for small or moderate earthquakes.

2 MECHANISM OF THE "IMPROVED FRICTION DAMPER(ONE UNIT)"

The "Improved Friction Damper" is composed of the "Friction Damper" itself, a "High-Damping Type Multi-Rubber", a force transfer shaft, and a guide plate(Fig.1). Initially in the "Friction Damper"(arms' angle is 60°), the friction force was set to be 15tonf. The "High-Damping Type Multi-Rubber" is extremely thin and consists of two layers. It was designed, when the "Friction Damper" starts sliding, to have a horizontal equivalent shear stiffness and deformation equaling to 17.9tonf/cm, 12.2mm respectively (total rubber thickness = 9.6mm, outer diameter = 538mm, inner diameter = 160mm). The upper flange of the Multi-Rubber is fixed to the upper structure and the ring-shaped guide plate (o.d. = 380mm, i.d. = 76mm) is attached to the lower flange. The force transfer shaft (o.d. = 75mm) penetrates into the hollow of the guide plate with clearance of 0.5mm. This shaft is connected to the upper structure and the "Friction Damper" itself through a sphere hinge.

When the external force exceeds the initial set friction force, the distance "d" between the two pins of the "Friction Damper" itself varies and the "Improved Friction Damper" starts sliding (toward either opening or closing direction)(Fig.2). The restoring force "Q" or the friction force "Frc^*" of the "Improved Friction Damper" always act on the line combining the center of the two pins (one is the joint between the force transfer shaft and the upper structure, while the other is that between the "Friction Damper" itself and the lower basement). Also the "High-Damping Type Multi-Rubber" deforms along this line while responding to the applied force "$F_D^*=(L/l)\cdot Frc^*$". Even if the ground moves in a different direction to this reference line, the whole "Improved Friction Damper" can pursue the structural motion by rotating on its pin which is connected to the lower basement. Hence, some restoring or friction force will act on the "Improved Friction Damper" corresponding to the distance between the two pins. Then the damper will deform. At the same time the friction force "Frc^*" is applied to the upper structure.

3 DYNAMIC VERIFICATION EXPERIMENTS OF THE HYSTERETIC CHARACTERISTICS

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3.1 Outline of the experiments

In the experiments conducted, all external forces were applied by a dynamic actuator which was vibrated using a controlled sine curve, whose amplitude of vibration and frequencies were considered to be parameters. The loading force from the dynamic actuator was transferred to all the parts of this system in the following order; the "High-Damping Type Multi-Rubber"→the guide plate→the force transfer shaft→the "Friction Damper". Points where measurements were taken during these experiments are shown in Fig.1.

3.2 Test results

The hysteretic characteristics having a large deformation(freq.= 0.2Hz, amp.= 8cm) were obtained by shifting the displacement away from the neutral axis. The test result is indicated as a solid line(Fig.3). The calculated skeleton curve of the "Improved Friction Damper" between the deformation "$(d^{*}+(L/l)\cdot\delta_D)$" and the acting friction force "Frc^{*}" is indicated as a thick line, and that of the "Friction Damper" itself between the distance "d^{*}" and "Frc^{*}" is as a dotted line(Fig.3). The test result agreed extremely well with the calculated one. The hysteretic characteristics(freq.= 0.2Hz,amp.= 3,5,8cm) in the vicinity of the initial condition are represented by a solid line(Fig.4). The calculated value(amp.= 8cm) is marked as ◉, the modified value considering the discontinuation at zero loading (about 2mm) caused by the clearance between the force transfer shaft and the guide plate is also marked as ○(Fig.4). The test result was very close to the calculated value while the "Friction Damper" itself is sliding. By considering the previously mentioned discontinuation at zero loading, even in the unloading path where the "Friction Damper" itself doesn't slide, the test result and the predicted value were still in good agreement.

The value of the equivalent shear stiffness and the equivalent viscous damping factor of the "High Damping Type Multi-Rubber" have been proposed by its maker(BRIDGESTONE.LTD.) as functions of the mean shear strain, and those obtained experimentally are shown respectively (Fig.5,Fig.6). In both figures, the calculated values are additionally expressed as dotted lines. The equivalent shear stiffness from the test results agrees well with the calculated value. Considering the difference in frequency, although the equivalent shear stiffness was found to be slightly larger as the frequency increased, the degree of difference became less and negligible for large amplitude vibration. The predicted value of the equivalent viscous damping factor is also close to that obtained experimentally and has little dependence on frequency.

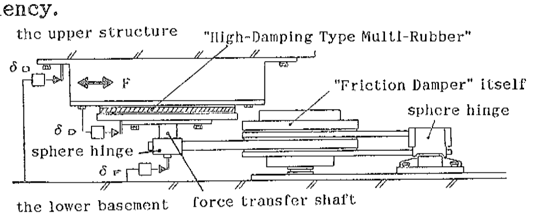


Fig.1 Outlook of the "Improved Friction Damper"

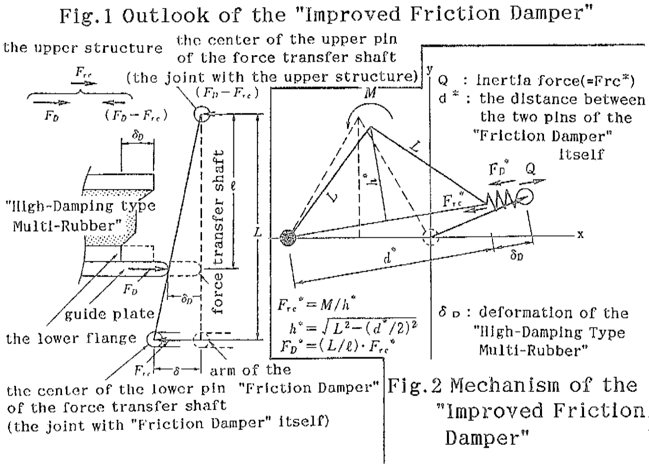


Fig.2 Mechanism of the "Improved Friction Damper"

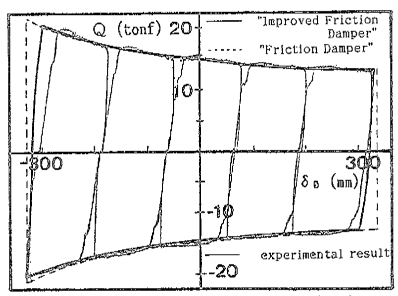


Fig.3 Hysteretic characteristics (with a large deformation)

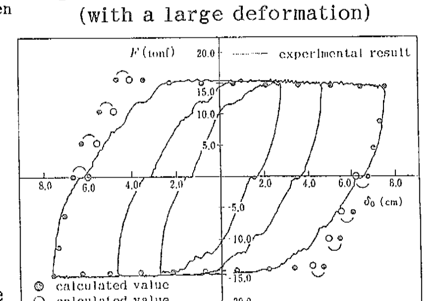


Fig.4 Hysteretic characteristics (vicinity of the initial condition)

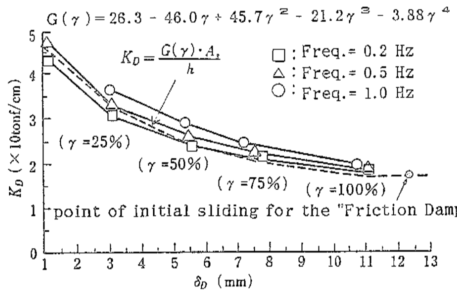


Fig.5 Equivalent shear stiffness ("High-Damping Type Multi-Rubber")

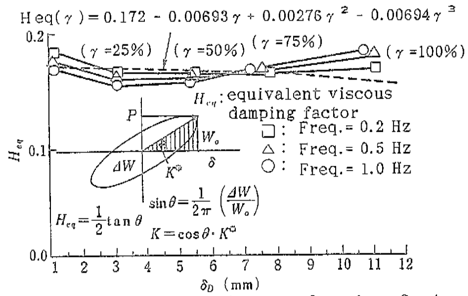


Fig.6 Equivalent viscous damping factor ("High-Damping Type Multi-Rubber")

4 DESIGN OF A MODEL BUILDING

4.1 Arrangement of the base isolation devices

A model building was designed, whose base isolation devices were composed of 8 "Improved Friction Damper" units and 8 multi-rubber bearings(Fig.7). These "Improved Friction Dampers" were allocated symmetrically along both the X-, and Y-axis in order to direct the applied force to the center of gravity of the building for the following two purposes. One is to allow the dampers' hysteretic characteristics to be independent of the direction of the building's movement and the other is to minimize the moment caused by the dampers in the horizontal movement.

4.2 The hysteretic characteristics of the dynamic analytical model(the 8 units combination)

Fig.8(1),(2) indicates the calculated hysteretic characteristics for the 8 units combination of the dampers when the direction of the building's movement deviates an angle of θ from the X-axis(Fig.7). This figure was obtained by combining the computed hysteretic characteristics of each "Improved Friction Damper". The direction of the building's movement doesn't necessarily coincide with the direction of the line connecting the two pins of each unit of the damper. In the cases of $\theta = 0°$, $\pm 45°$ or $\pm 90°$, these two directions of 2 units which are located along the same line of the building's movement are identical. And the other 2 units located along the line perpendicular to the movement's direction don't develop any restoring forces (or friction forces) but only rotate. However, some little force arises in the direction perpendicular to the movement's direction(Fig.8(2)). It is caused by the divided component of the restoring force (or the friction force) developed in the units whose lines connecting the two pins are not parallel to the movement's direction.

As a single unit, the "Improved Friction Damper" can deform before either its arms open to the full extent (distance between the arms = 2L) or its arms close to contact each other (distance = $L(1-\sin\theta/2)$)(Fig.9). For the 8 units combination, the friction force acting on the upper structure can be regarded as constant while the distance between the two arms of the closing unit exceeds L/2. As the 2 units of the dampers located along the line perpendicular to the direction of the building's movement merely rotate, the friction force arises in these dampers is very small. And the 4 units located on the other 2 lines with a $\pm 45°$ deviation angle from the movement's direction contribute the friction force of only $1/\sqrt{2}$ times the real acting magnitude "Frc*"(Fig.10). Hence the total friction force carried by the 8 units combination is about $(2+2\sqrt{2})$ times the set value of a single friction damper.

By considering only the restoring force of the "High-Damping Type Multi-Rubber", when the 6 units of the dampers start sliding (excluding the 2 units, whose line connecting the two pins is perpendicular to the movement's direction), the equivalent shear stiffness of the 8 units combination can be calculated as follows(Fig.11); $(Frc/\sqrt{2})/(\sqrt{2}\delta) = (Frc/\delta)/2$ per each unit of the 4 units arranged along the two lines with a $\pm 45°$ deviation angle from the movement's direction. So the equivalent shear stiffness operating on the upper structure by the 8 units combination, was found to be 4 times that of a single unit. The relation between the friction force "Frc" at the center of the pin beneath the shaft and the restoring force "F_D" of the "High-Damping Type Multi-Rubber" can be expressed as $F_D = (L/l)\cdot Frc$ (Fig.1).

The relation between the displacement at the center of the pin "δ" and that of the "High-Damping Type Multi-Rubber" "δ_D" can be expressed as $\delta_D = (l/L)\cdot\delta$. And the stiffness acting on the system is obtained from the equation $Frc/\delta = (l/L)^2\cdot K_D$. The calculated restoring force and the equivalent shear stiffness prior to the dampers sliding out are displayed and compared for the 8 units combination and the total of 4 sets of the "High-Damping Type Multi-Rubber"(Fig.12(1),(2)). These values are almost identical and the equivalent elastic periods of these two cases are close to each other. As a result, the hysteretic characteristics for the 8 units combination can be idealized as shown in Fig.13.

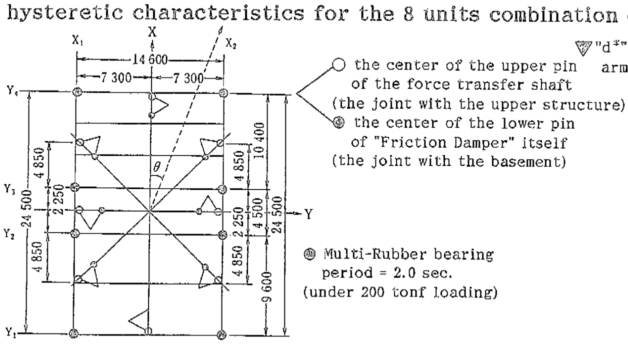
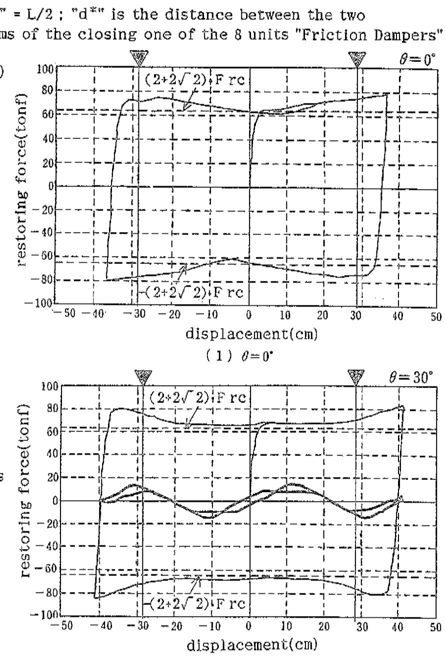


Fig.7 Arrangement of the base isolation devices



—— The divided component of the restoring force which arises in the direction perpendicular to that of the building's movement

Fig.8 Hysteresis characteristics (the 8 units combination)

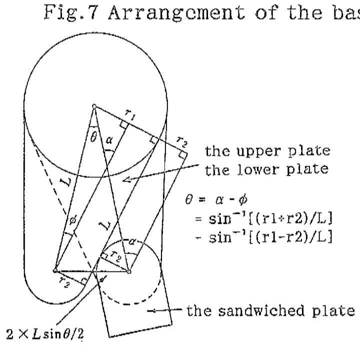


Fig.9 Limit state of "Friction Damper"

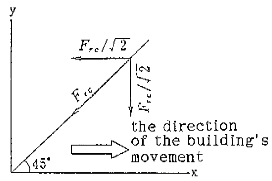


Fig.10

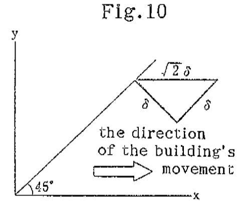
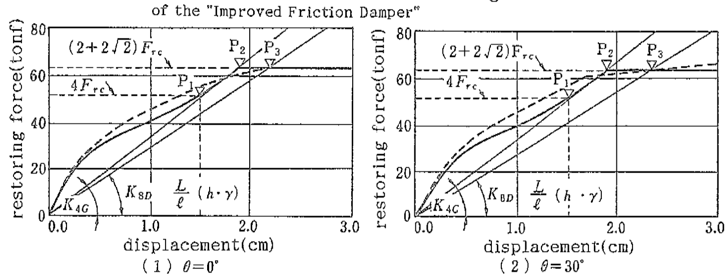


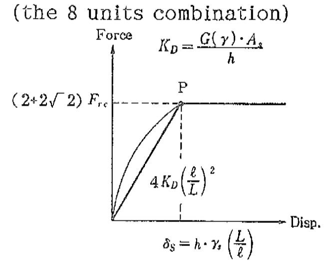
Fig.11

—— dynamic analysis
······ 8 units combination of the "Improved Friction Damper"



K_{8D} : equivalent shear initial stiffness (8 units combination of the "Improved Friction Damper")
K_{4G} : equivalent shear initial stiffness (4 sets of the "High-Damping Type Multi-Rubber")
P_1 : design point for the "High-Damping Type Multi-Rubber"
P_2 : point of initial sliding for the dynamic analytical model(cf.Fig.15)
P_3 : point of initial sliding for the 8 units combination of the "Improved Friction Damper"
T_{8D} : equivalent elastic period at point; P_3 = 1.27sec.(θ=0°,45°,90°) (multi-rubber bearings + 8 units combination of the "Improved Friction Damper") = 1.30sec.(θ=15°,30°,60°,75°)
T_{4G} : equivalent elastic period at point; P_2 = 1.21sec. (multi-rubber bearings + 4 sets of the "High- Damping Type Multi-Rubber")

Fig.12 Comparison of the restoring forces and equivalent shear initial stiffness (for the 8 units combination and 4 sets of the "High-Damping Type Multi-Rubber")



P : point of initial sliding for the "Friction Damper"
F rc: preset friction force for the "Friction Damper"
δs : displacement at the point; P
K_D : equivalent shear initial stiffness of the "High-Damping Type Multi-Rubber" at the point; P
As : shear area of the "High-Damping Type Multi-Rubber"
h : total thickness of the rubber
γ : mean shear strain in the rubber
G(γ): equivalent shear stiffness corresponding to the mean shear strain

Fig.13 Idealized restoring force (skeleton curve) of the 8 units combination of the "Improved Friction Damper"

5 EARTHQUAKE RESPONSE ANALYSIS OF THE MODEL BUILDING

5.1 Eccentric distance

Generally, in a base isolation system using multi-rubber bearings, the dampers are arranged symmetrically to both the center lines and the bearings are chosen to make each contribution of its stiffness to the sustained load uniform. Hence the theoretical center of rigidity is expected to coincide with the center of gravity, and torsion caused by eccentricity can be neglected. But in reality some eccentricity may exist due to some factors such as non-uniformity of the live load, and uneven concrete weight. For this reason an earthquake response analysis, considering 2-degrees-of-freedom namely horizontal displacement and rotation in the horizontal plane, was conducted and the effect of the eccentricity on the base isolated structures was investigated by assuming a moderate eccentric distance.

The loadings for the model building, which has a rigid body(Fig.7) is as follows;

total weight　　dead load　　live load(for calculating seismic force)

1815.4 tonf = 1750.7 tonf + 64.7 tonf

By assuming that the entire live load of 64.7tonf is concentrated on the area supported by a multi-rubber bearing located at coordinates (X2,Y4), the eccentric distance "e" is 71.1cm corresponding to almost 3% of the longer side of the building(Fig.7). But the eccentric distance is redefined to be 122.5cm(5% of the longer side) by taking several other additional factors into consideration. For simplification the eccentricity was limited to only the Y-axis. The load carried by the multi-rubber bearings on the Y4 line increased 43.5tonf(about 2.5% of the total weight) and decreased the same amount on the Y1 line. So there was no overall change in the total weight of the building.

5.2 Analitycal method

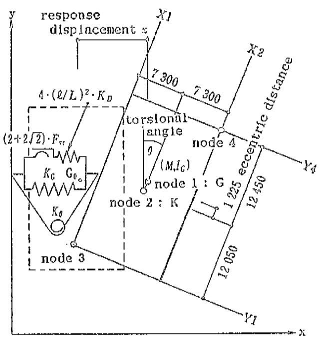
The earthquake response analysis was based on the 2-degrees-of-freedom system(Fig.14). A rigid body model was adopted, which concentrates the mass and moment of inertia at the center of gravity. Furthermore the plane geometry of the building is taken into consideration through the nodal points at the edge of the building. The non-linear horizontal spring used in the analysis was modeled by combining a "Improved Friction Damper" and a multi-rubber bearing in parallel. The "Improved Friction Damper" consists of the two parts, namely a "High-Damping Type Multi-Rubber"(under the modified-bilinear hysteresis law) and a "Friction Damper" itself, which maintains a constant friction force, connected in series (Fig.15). After determining the friction force to be $(2+2\sqrt{2})\cdot Frc$, 63.54tonf(= 0.035W), the 20% force was applied both up and down to consider the effect of variation of the friction force due to factors such as rust and adhesion. The equivalent initial period of the system from only the horizontal spring at the point P where the "Friction Damper" starts sliding was designed to be approximately 1.2sec.. The linear rotational spring was identified with the torsional stiffness from only the multi-rubber bearings since the "Improved Friction Dampers'" arrangement can't resist torsion. Damping was given in proportion to strain energy by assuming the damping factor of each member to be 3% for both the horizontal and rotational springs of only the multi-rubber bearings. This coincides with another assumption that the damping factor is considered to be 3% for both the first and the second vibration modes when the building is sliding(Fig.16). Ground motion was input only in the X-axis. EL CENTRO(NS) 1940, HACHINOHE(NS)/(EW) 1968, TAFT(EW) 1952 and a simulated earthquake obtained by matching the acceleration response spectrum (damping factor 5%) to the dynamic coefficient;Rt for intermediate soil conditions according to "Japanese Structural Calculation Guidance" were chosen as input waves. Two different input levels, level 1(25kine) and level 2(50kine) were considered in these analyses. As a computing method the newmark-β (β=1/4) method was executed by the direct integration with a time increment step of $\triangle t$=1/2000 sec..

5.3 Result of the earthquake response analysis

For the 2-degrees-of-freedom system, in large input level of the ground motion, a larger torsional moment can be caused due to the increment of the horizontal restoring force. Hence the maximum response displacement at the edge of the building(by the horizontal and torsional displacement) becomes larger compared to that at the center of rigidity;K(by only the horizontal displacement). But the extent of the increment is about 20% at most(Fig.17). The maximum response displacement at the edge of the building shows good correlation with the maximum response torsional angle although they don't occur simultaneously(Fig.18). The response torsional angle when the maximum response displacement at the edge of the building is achieved is evaluated to be equal to half of the maximum one. The difference in the input ground motion has more influence on both the maximum response values than the difference in the friction force has.

6 CONCLUSIONS

① Hysteretic characteristics of the "Improved Friction Damper" obtained from the test results agreed very well with calculated ones(Fig.3,Fig.4).
② The equivalent shear stiffness and equivalent viscous damping factor of the "High-Damping Type Multi-Rubber" can be predicted very well by the proposed equations, and were found to have little dependence on both the frequency and amplitude of vibration(Fig.5,Fig.6).
③ The "Improved Friction Damper" demonstrated some hysteresis even for small amplitude vibration when the "Friction Damper" still doesn't slide. Accordingly the hysteretic energy dissipation can be expected even for small or moderate earthquakes(Fig.4).
④ The filtering function of cutting high frequencies is expected by setting the equivalent shear initial stiffness of the "Improved Friction Damper" properly. In result, it is expected that any objective building using the optimum Base Isolation System can be designed.
⑤ For the model building discussed in this paper the horizontal maximum response and the torsional maximum response caused by eccentricity didn't occur simultaneously. And the effect of the eccentricity was found to be comparatively small(Fig.17,Fig.18).



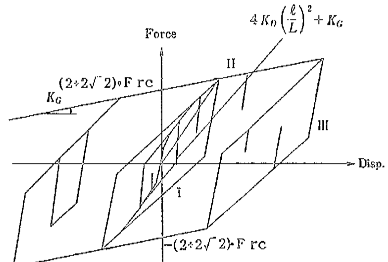
G : the actural center of gravity
Go : the original center of gravity
K : the center of rigidity

M : total weight(1815.4 tonf)
I_G : moment of inertia(236.1x10^7 tonf·cm^2)
θ : torsional angle(rad)

K_G : linear spring equivalent for the horizontal stiffness of the multi-rubber bearings
K_θ : linear spring equivalent using only the torsional stiffness of the multi-rubber bearings

$4\cdot(l/L)^2\cdot K_D$: non-linear spring equivalent using the "High-Damping Type Multi-Rubber" considering the effect of the force transfer shaft(8 units combination of the "Improved Friction Damper")
$(2+2\sqrt{2})\cdot F_{rc}$: friction force(8 units combination of the "Improved Friction Damper")

Fig.14 Dynamic analytical model



I : State before the "Friction Damper" itself starts sliding [friction force<$(2+2\sqrt{2})\cdot F_{rc}$] ,restoring force of the "High-Damping Type Multi-Rubber" + restoring force of multi-rubber bearings
II : State when the "Friction Damper" itself is in the process of sliding [friction force=$(2+2\sqrt{2})\cdot F_{rc}$] ,friction force [$(2+2\sqrt{2})\cdot F_{rc}$] + restoring force of multi-rubber bearings
III : State when the "Friction Damper" itself is still in the process of stopping and some deformation remains in the "High-Damping Type Multi-Rubber" [friction force<$(2+2\sqrt{2})\cdot F_{rc}$] ,restoring force of the "High-Damping Type Multi-Rubber" at the maximum strain level under steady state vibration + restoring force of multi-rubber bearings

Fig.15 Hysteresis characteristics of the horizontal non-linear spring

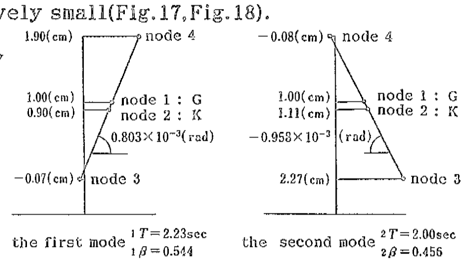


Fig.16 natural periods and modes (when "Friction Damper" is sliding)

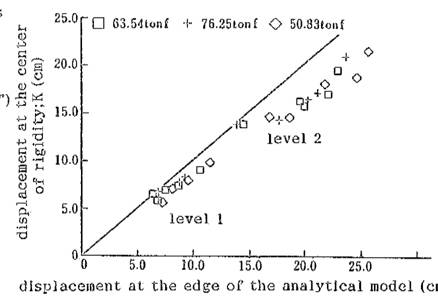


Fig.17 Comparison of two maximum horizontal response displacement

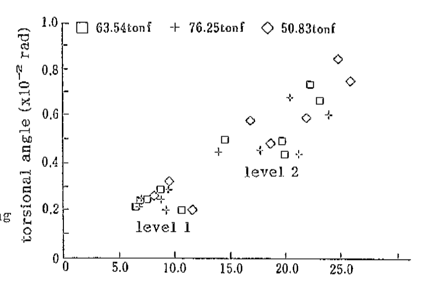


Fig.18 Comparison of two maximum response values