0308

A DEVELOPMENT OF A NEW TECHNOLOGY FOR BASE-ISOLATED BUILDINGS USING CROSSED LINEAR BEARINGS

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SUMMARY

This paper presents the new base-isolated system called Crossed Linear Bearings (CLB hereafter) which enables isolation application to lightweight houses or high-rise buildings or cylindrical structures. This system was developed to overcome the "restriction on application" which is caused by engineering problems such as buckling, or tensile failure when using conventional multi-rubber- bearing systems. Many experimental data or earthquake records have been examined in comparison with theory and analysis. The system demonstrated effective performance on response control, and it was verified that CLB has sufficient ground to be put into application. Based on this recognition, several buildings have already been constructed utilizing CLB systems. This paper also introduces some examples of CLB applied to buildings.

INTRODUCTION

As Japan is an earthquake-prone country, it is crucial to secure seismic safety in construction of structures. Recently it has been pointed out in the discussion of building seismic safety, that seismic technology has now stepped into a new phase to aim at "maintenance of future safety" and "economic loss prevention" after the earthquake as well as aiming at security of human lives. Excellent performance of base isolation technology observed in Hanshin-Awaji earthquake suggests new roles for seismic technology of the next generation. However, it is also an undeniable fact that current base isolation technology using mainly rubber bearings faces limits in application for several dynamic reasons. The authors find that the main cause of application limit is due to the fact that excessive capacity (i.e. load bearing capacity, large displacement capacity and damping capacity) is expected of the isolators even though the isolators have elasto-plastic characteristics. In order to find more opportunities for isolator application, compressive stress should be released from isolators. This can be actually realized by separating isolator function, which is the main thesis of this report. Crossed-Linear Bearings System-CLB was developed to achieve this concept. The following is the goal of this system:

▪Applying isolation to lightweight structures such as wooden houses or steel structured houses
▪Isolation of high-rise or tower buildings
▪Isolation on the long period locations such as soft ground

1. CLB BASE ISOLATION SYSTEM

1.1 The limit to first generation base isolation system.

In the first generation base isolation, rubber bearing fulfilled three necessary functions: building support, restoration, and energy dissipation. However, this type of isolation has the following problems: Though increase of compressive stress in order to increase its period. Increase of axial load may reduce the isolator's critical displacement and cause unstable phenomenon such as buckling. Such a limit makes it difficult to apply rubber-bearing isolators to lightweight buildings. On the other hand, as for tensile stress, changes in axial compression due to overturning moment or vertical earthquake may lead to changes in shear rigidity as well as excessive tensile strain on the rubber bearing. As such, it would make it difficult to apply isolation to high-rise buildings

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or tower buildings. Isolators within dampers or high-damping rubbers change their hysteresis characteristics depending on strain rate, displacement or hysteresis history**.** Currently development of hysteresis models solely depends on developers of the isolator, and response analysis is not consistently reliable. This hinders standardization of response analysis. Hence, it is significant to develop next generation isolation technology to cope with the above problems.

1.2 Characteristics of CLB system.

CLB Base Isolation (distributing those functions of the base isolator for separate purposes) has the following characteristics:

1) Supporting load system

Photo-1 indicates an example of CLB installation, and Figure-1 indicates its internal mechanism. The device consists of steel roller blocks and a rail with grooves for rolling motion. There are steel balls between the blocks and the rail, and the balls rotate within the blocks. The blocks operate with low rolling frictions. The CLB isolator is allowed to move in a plain by setting the devices in cross directions. Diameter of the ball, effective pieces and number of linear devices determines the load supporting capacity of CLB. Figure-2 indicates various performance tests conducted on the CLB. The following report describes CLB's dynamic characteristics and performance of auxiliary device and discusses key points in design of the CLB.

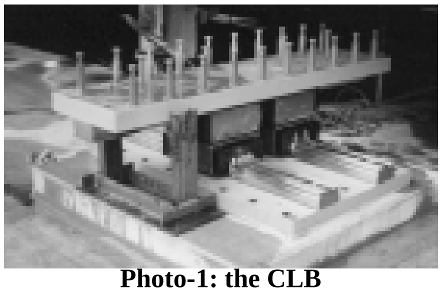

Photo-1: the CLB

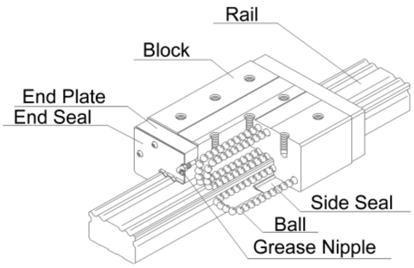

Figure-1: mechanism of The CLB

a. Friction characteristics Conventional elastic sliding bearings change the coefficient of friction depending on bearing stress and relative velocity. Figure-3 shows the relation of allowable load Po=250tonf with CLB's displacement and coefficient of friction. Coefficient of friction does not depend on velocity, and its value is about 1/10 of that of elastic sliding bearings. Further, Figure-4 indicates the relation between axial compression ratio (axial load P/allowable load Po) and coefficient of friction. As axial compression ratio increases from 0.2 to 1.2, coefficient of friction changes from 0.002 to 0.01. The change, however, is extremely small. The coefficient of friction is determined solely by bearing load. This indicates that it is possible to install isolators with different bearing load, and the performance does not depend on displacement of isolators. Coefficient of friction is calculated by the formula in the figure. The value in the formula is determined whether the curvature of the groove is close to 51% or 52% of the ball radius The value becomes smaller when the groove is 52%, closer to plain dimension. Such characteristics of friction are caused by rolling frictional force by (Heathcote slip in Figure-5)**.** The friction can be obtained theoretically by formula (1) as follows:

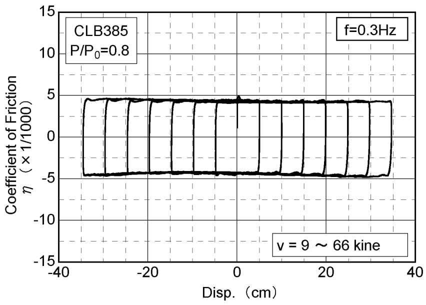

Figure-3:disp. & friction

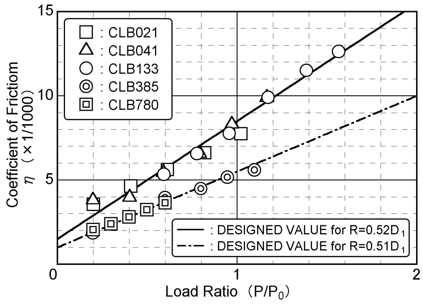

Figure-4:P/P$_0$ & friction

$$\eta = \frac{F_R}{W} = k_1 \left(\frac{W^{1/3}}{R^2} \right)^2 \qquad (1)$$

Thereupon, F_R : rolling friction force [=k($W^{5/3}/R^{4/3}$)] of 1 steel ball.

W : load which affects 1 steel ball.

R : steel ball radius . K,k_1 : proportion constant.

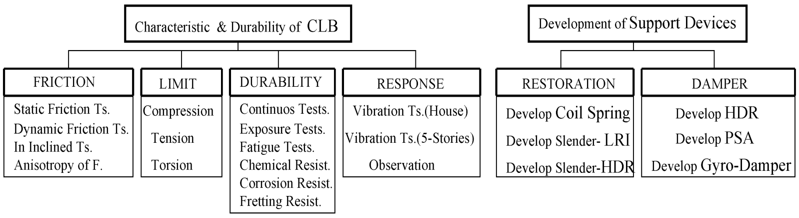

Figure-2:experiment lists of CLB

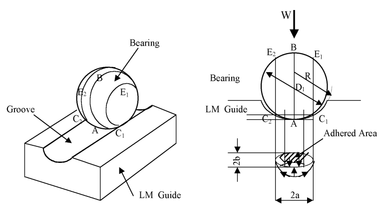

Figure-5:heathcote slip

The formula (2) below indicates the relation between the coefficient of friction and the contact stress σab

$$\eta = k_2 (\sigma_{ab})^2 \qquad (2)$$

between steel ball and the groove.

Thereupon, σab : [=W/πab=k_3(W/R^2)$^{1/3}$] contact stress. a,b : length and breadth of tangential ellipse,

K_2 and k_3 : proportion constant.

Both formulas show that coefficient of friction η is the same value if the contact stress σ_{ab} is the same regardless of the diameter of the steel ball. Therefore, isolators for lightweight buildings and heavy weight buildings show about the same coefficient of friction for axial compression ratio.

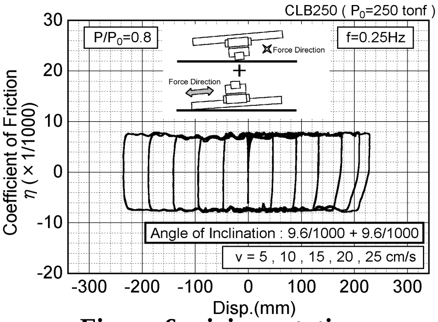

Figure-6: giving rotation

This CLB adopts about σ_{ab}= 4,200 MPa from ISO standard as design contact stress upon allowable load Po.

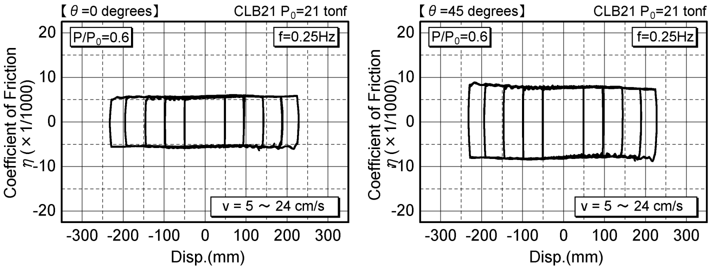

Figure-7: anisotropy of the CLB

b. Frictional property in an inclination. CLB isolators need to function even when there is execution error, or when building foundation or supported portion rotates. Rubber pads are used for stress relaxation in order to cope with such rotation. The coefficient of friction at such inclination is indicated in Figure-6. It shows the relations between displacement and coefficient of friction when approximately 1/00 rad. inclination is applied to the rail axis and right angle directions. The coefficient of friction increased only by 20% compared with the case without inclination, and it was confirmed that CLB fully maintained it isolation function even at the time of rotation. Tolerance for leveling error at the time of isolator installation and the rotational angle of the isolator during earthquake is specified according to the result of the above test.

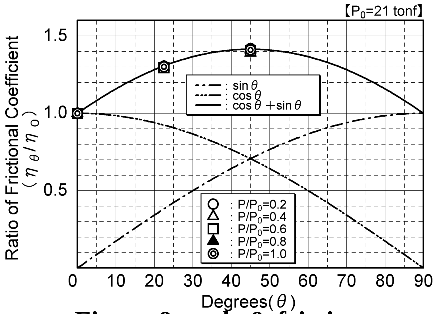

Figure-8:angle & friction

c. Anisotropy Ground motions are applied to single or double crossed CLB isolators at a certain input angle θ. Figure-7 indicates the relation between apparent coefficient of friction η_θ and displacement under such condition. Figure-8 indicates the relation between η_θ/η_0 (defined as friction coefficient ratio) and input angle θ. It is found that friction characteristics in the X and Y directions of CLB are independent, and apparent coefficient of friction η_θ in the θ direction can be obtained by geometrical addition.

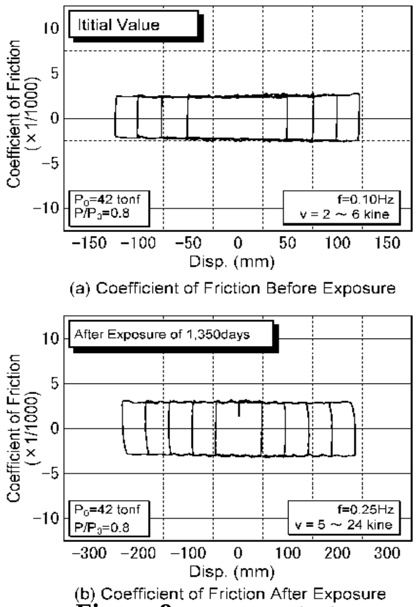

Figure-9: exposure test

d. Exposure limit test Figure-9 indicates the relation between the coefficient of friction and the displacement for the CLB underwent during 1350 days exposure test. Although slight rust was found on 70% of the rolling plain treated with grease as corrosion proofing, coefficient of friction only increased by 20% from the initial value. Thus, considering the actual environment, changes by exposure can be ignored.

e. Critical characteristic (compressive strength) After a compressive strength test, as for design criteria, N_L<=Po is adopted for sustained load**.** For actual earthquake**,** N_{EL}<=2Po is adopted for vertical earthquake, and critical vertical compression is set as N_{max}<=3Po. **(tensile strength)** The tensile strength of the CLB can be determined by the strength of the bolt connecting the blocks. **(torsion strength)** The torsion strength of the CLB was confirmed to be more than the fracture strength of the connecting bolts.

f. Vertical restoration Stiffness of the CLB can be obtained by adding the theoretical solution of elastic contact to the theoretical solution of plastic contact. Stiffness of the CLB with isolator and rubber shim can be treated as a series spring. Double type or parallel type are treated as parallel spring. Figure-10 indicates the CLB's restoration character in the vertical direction. The order of the stiffness of the CLB calculated from the above test data or theory are approximately the same as those of Lead Rubber Isolation. This suggests the possibility of a hybrid base isolated structure.

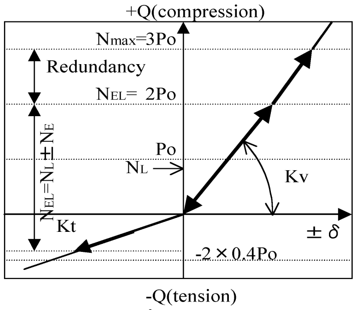

Figure-10: vertical restoration

2) Restoration mechanism

The building supported by CLB isolators seemingly becomes a period free building. It is the task of the restoration device to provide such a building with certain characteristics of period. Since the CLBs support all upper structure loads, it is possible to release the restoration device from bearing stress. Thus, it is even possible to apply very slim high damping rubber bearing (HDR hereafter) or LRI and linear coil spring as shown in picture 2. As result, it is possible to achieve an isolated building with a long period of over 5 seconds, and an ideal concept can be also realized. Figure-11 shows the hysteresis characteristics of HDR-200*φ* used as a restoration device for lightweight structures such as residential building. As this device does not take axial compression, tensile stress can be developed in the vertical direction according to the response displacement. However, such stress is only about the elastic modulus (E) of rubber material, which causes no internal break. Hysteresis curve of this isolator is also confirmed successfully.

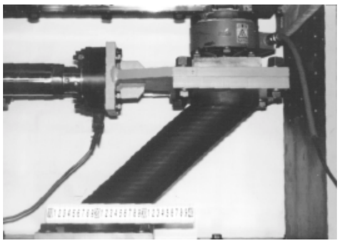

Photo-2: HDR-200

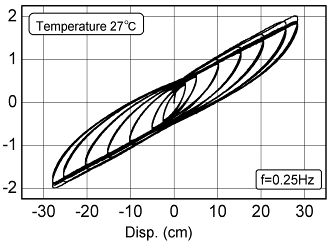

Figure-11: HDR's loop

3) Damping mechanism

It is a matter of course that a conventional LRI can be installed on heavy structures for restoration and damping. When only a damping function is required, it is easier to use devices without stiffness such as viscous dampers. Such devices are also advantageous in terms of reducing velocity response. Figure-12 indicates a viscous damper developed through this technology. Both devices are developed to realize the " concept of amplification and increment of damping capacity". The PSA (Preeminent Shock Absorber) in Figure-12(a) is different from conventional dampers using orifice effects. The device connects oil spaces at both ends through a slim pipe and increases viscous resistance by the increase of liquid velocity. It can also adjust its damping capacity according to the viscosity of the viscous material and diameter and length of connecting pipe. Figure-13 and 14 show displacement and damping force relations and velocity and damping force relations. These indicate the device has stable and greater damping performance without effects of stiffness.

$$F_P = A_C (P_1 - P_2)$$

$$@\ @\ \frac{A_C}{\pi \text{¥} R^2}(2\pi R L_O)\text{¥}\left[\alpha\mu\left\{(3\beta+1)\frac{V_C A_C}{R^3\pi\beta}\right\}^3\right] \quad (3)$$

Thereupon, Ac : rum taking pressure area R : hole radius of tube, Lo : effective length of tube.

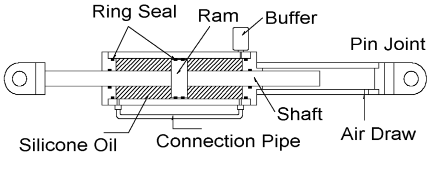

Figure-12(a): PSA

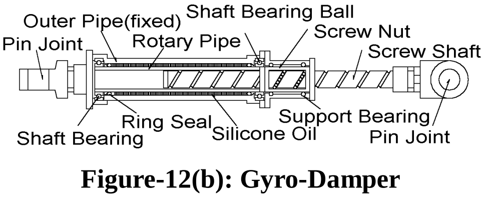

Figure-12(b): Gyro-Damper

μ: viscosity of the viscous fluid, Vc : velocity of lot, α,β: :nonlinear constant.

The Gyro-Damper indicated in Figure-12(b) converts linear motion into rotational motion by use of a ball screw. By such motion, it increases velocity and amplifies damping capacity.

Figure-15 and 16 indicate the hysteresis loop and damping property of this device.

Damping force is calculated by formula (4). It is found that the damping force is increased as the velocity

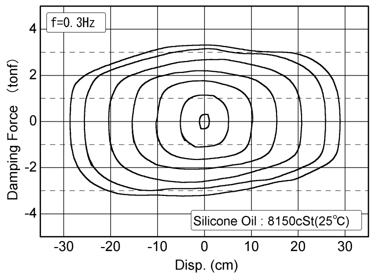

Figure-13: PSA's loop

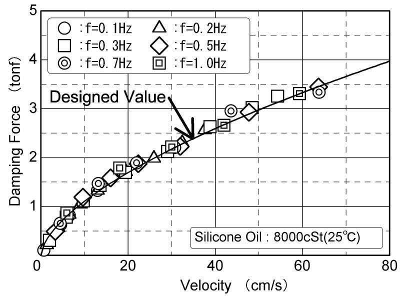

Figure-14: PSA's force

increases in response to the relations between lead and inner pile.

$$F_P = {}_f\mu(V_S,t)\yen\left(\frac{d(S\yen V_n)}{dy}\right)S\yen A \qquad (4)$$

Thereupon, $_f\mu(Vs,t)$: viscosity function (≡f(Vs,t)) of the viscous fluid, dVn : velocity of shaft,

S : amplification ratio of velocity(=2πr/Ld), t : temperature, R : outside radius of inner cylinder,

Ld : lead of screw, dy : shear clearance, A : shear effective area, Vs : velocity of shearring strain (= dSVn/dy).

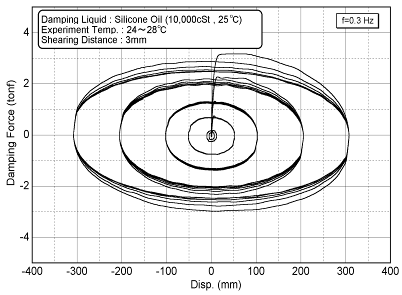

Figure-15: G-damper's loop

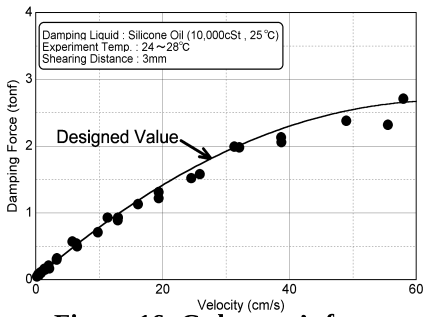

Figure-16: G-damper's force

2. RESPONSE

The dynamic properties of the earthquake observation building using the CLB isolator system are discussed hereafter with the report of vibration tests and earthquake observation.

2.1 Outline of the building

Photo-3 shows the appearance of the earthquake observation building. The building is a lightweight (40ton in total) steel frame 5-story tower building with aspect ratio =4.18. The building consists of two types of isolation systems: CLB as primary isolator, and coil spring as restoration device. No damping system has been installed in the building. The equivalent periods for the building are T=2.3 seconds and 4.7 seconds. The observation building enables its movable foundation to apply forced vibration. It also functions as a conventional earthquake resistant when the above isolation systems are not in use.

Photo-3: CLB building

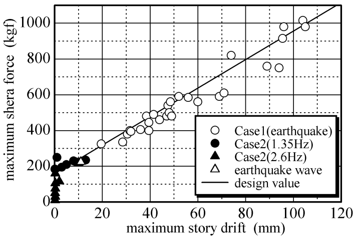

Figure-17: relative disp. & force

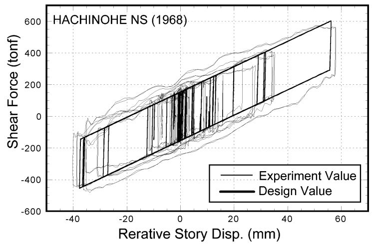

Figure-18: disp.-load curve

2.2 Inspection of response condition

Figure-17 illustrates the relationship between relative story displacement and shear force of the CLB as a result of the compulsory vibration test. Figure-18 indicates the displacement-load hysteresis observed in isolated floors. Figure-19 compares the data observed during the Ibaragi earthquake (M=5.5,'96.12/21) and the response analysis for T=4.7 isolation. Each property observed in the earthquake proves to be consistent with the design value from micro-scale to large-scale displacement. As a result, it was proved that this method of reducing response velocity was extremely effective. Figure-20 demonstrates the large-scale earthquakes such as Hyougo -ken Nanbu earthquake (M=7.2, '95.1.17) to simulate as input to buildings. The effect of damping was also examined by comparing responses in different condition; response with damping and responses without damping. Each component of vibration showed extremely effective damping. Effects of damping are evident in the velocity and displacement response. It was found that the damping restricts the response increase triggered by longer period in the isolation system. However, there is little difference in each relative story displacement depending on damping capacity. It is understood that only isolated layers are subject to such damping effect. There is no considerable difference in the components of acceleration in relation to the extent of the damping capacity when isolation sufficiently prolongs the period of the building.

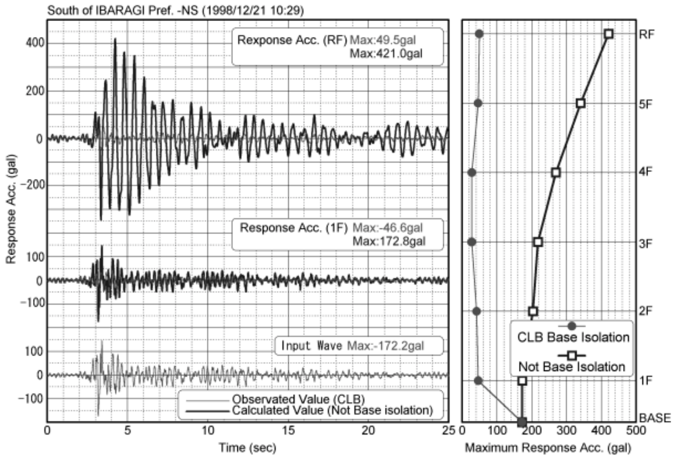

Figure-19: comparison with observed value & analysis

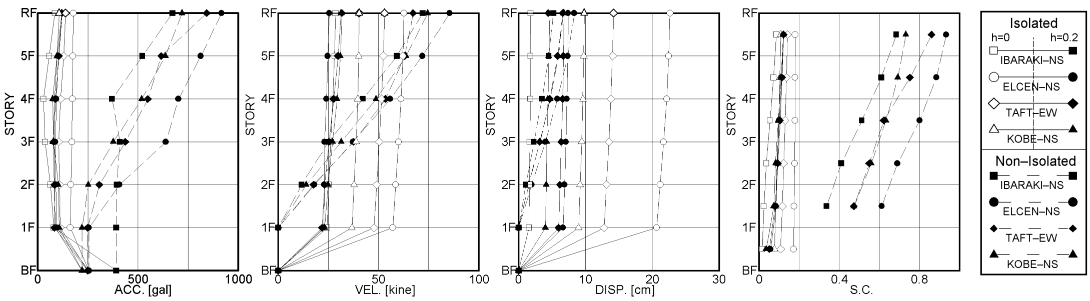

Figure-20: result of analysis

3. DESIGN AND CONSTRUCTION

The CLB has been applied to 10 building projects, which were recognized and listed as isolation projects by the Japan Isolation Committee, as it is shown in table 1. The CLB has been applied not only to building projects but also to floor isolation or exhibition platforms. These are the trends of versatile application supported by a variety of specifications, as it is shown in table 2. In this paper, a 3-story wood base isolation residence is introduced as a design example (No.4 of Table-1)

Table-1: the CLB structures

	Name of Building	Site	Structure	Weight (tonf)	E. Period (sec)	Isolator	Restoration & Damper	Evaluation Number
①	Observed Build.	TOCHIGI	S-5F	40.0	4.68	CLB41	Spring	
②	Y co. Office	YAMAGATA	S- 3F	5,133.0	4.62	CLB250	LRI(800-1200φ)	BCJ-B289
③	Tr Residence	TOKYO	RC- 3F,B-2F	3,920.0	4.37	CLB250(‡)	HDR(900φ)	BCJ-B377
④	Kb Residence	TOKYO	Wd-3F	83.4	3.77	CLB21	LRI(100φ)	BCJ-B413
⑤	K1 Residence	SAITAMA	LS-2F	94.2	4.20	CLB21,31	LRI(100φ)	BCJ-B435
⑥	Sk Residence	TOKYO	Wd-1F	74.6	3.50	CLB21	HDR(100φ)	BCJ-B492
⑦	Tn Residence	KANAGAWA	S-2F	126.5	3.93	CLB21	HDR(100φ)	BCJ-B541
⑧	D co. Office	SHIZUOKA	S-5F	1,794.0	4.00	CLB133(‡)	LRI(700φ)	BCJ-B563
⑨	Ie Residence	TOKYO	S-2F,B-1F	141.1	4.52	CLB61	HDR(200φ),PSA5-350	BCJ-B612
⑩	Y Emergency C.	HYOUGO	RC-5F	7,772.0	4.61	CLB385(+,‡)	LRI(1000-1200φ)	BCJ-B614
⑪	Tk Residence	SAITAMA	S-3F	223.0	4.37	CLB11	HDR(200φ), Gyro15-350	BCJ-B646

Table-2: list of the CLB

Type of Device	SINGLE(+)		DOUBLE(‡)	PARALLEL(#)
	Compression	Tension	Compression	Compression
CLB17	16.5	11.7	33.0	66.0
CLB21	21.4	15.2	42.8	85.6
CLB31	31.0	22.0	62.0	124.0
CLB41	41.0	29.1	82.0	164.0
CLB61	61.2	43.5	122.4	244.8
CLB133	132.7	94.2	265.4	530.8
CLB250	250.0	88.8	500	1000
CLB385	385.0	136.7	770	1540
CLB785	785.0	276.9	1570	3140

3.1 Upper structure

The upper structure for the CLB building is constructed by a wood-frame 2 x 4 method (Figure-21). The design wind load exceeds seismic force of earthquake in short –line direction of the building. However, the building has horizontal load-carrying capacity 3.5 times design seismic force in short line direction and 3.1 times design force in long line direction. The members are designed in compliance with allowable stress design.

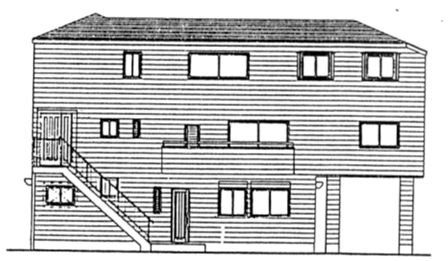

Figure-21 wooden house with theCLB

3.2 Foundation, Intermediate member

The difference between a conventional residence and the CLB isolated residence in base-isolation foundation is that the vertical load is supported in the form of point support rather than line support. It is also necessary to apply special structural members in the intermediate frame in order to secure in or out of plane rigidity. The stress developed during an earthquake such as horizontal force or eccentric moment needs to be handled in the beam of the foundation connecting to individual footing. Recently a flat foundation has been often applied for that purpose.

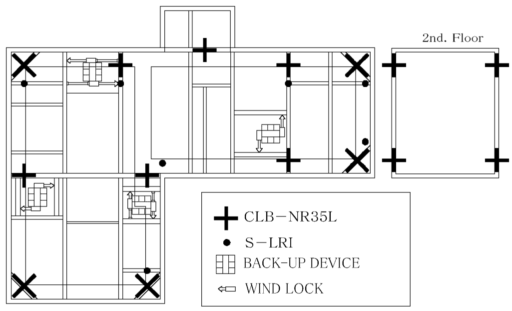

Figure-22: devices plan

3.3 Isolator and restoration

15 CLBs have been installed in the building (11 CLBs to the 1st floor and 4 CLBs to steel framework in the 2nd floor), and the dynamic coefficient of friction is 0.004 in the 1st floor and 0.0035 in the 2nd floor. Seismic gap at the time of earthquake is designed as 30cm. As LRI is not subject to axial force, 7 LRIs were installed for restoration and damping functions to the positions where no torsion vibration by eccentric force will develop. Lead plugs for LRI were designed to reach yield strength by wind pressure at the speed of approximately 20m/s. Figure-22 shows the layout of the devices, and Figure-23 illustrates the hysteresis loop and model analysis.

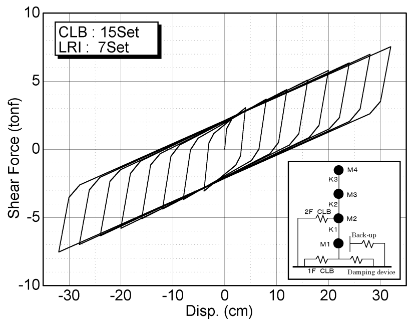

Figure-23: design loop

3.4 Back-up equipment

Backup system controls response displacements exceeding the allowable displacements (30cm in this case) which occur upon very sever earthquake motion. This system adopts V-shape back up material made of rubber. It limits displacements of the isolated layer within seismic gap by gradually providing stiffness once relative displacement between base and building exceeds 22.5cm.

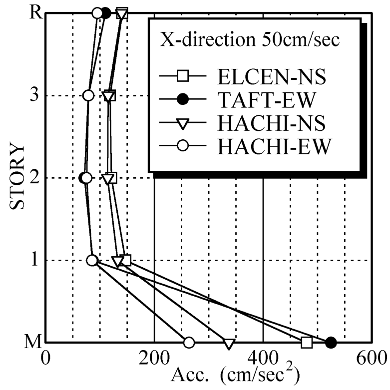

Figure-24: response nanlysis

3.5 Wind lock system

This building moves upon strong wind of over 20m/s. To ensure better living condition and usability against strong wind or earthquake, 8 manual type oil jacks were installed as wind-lock systems.

3.6 Earthquake response condition

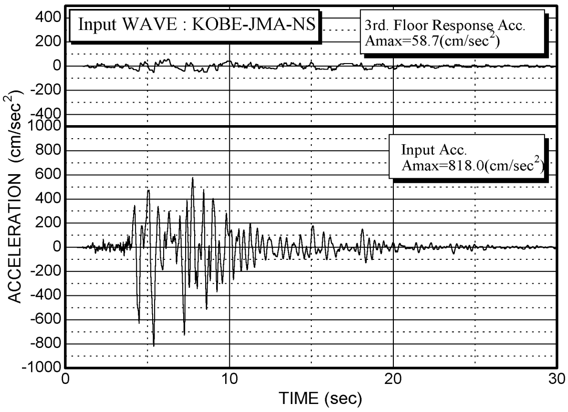

Figure-25: response time history

Figure-24 demonstrates models and maximum response in earthquake response analysis. Figure-25 shows time hysteresis of the response wave. Maximum response acceleration will reach in the range of 78.5~118.7cm/s^2 against ground motion input around V=50cm/s equivalent, and it will be reduced by approximately 1/3~1/7 of the maximum acceleration input. As for large and heavy structures, innovative isolation methods have been applied aiming at longer period and design flexibility; the CLBs are used in combination with conventional rubber bearings (No.8,10–table 1). Viscous damping function is also applied (No.9,11 of table 1) along with CLB systems.

CONCLUSIONS

The CLB base-isolation system has been developed as a new system to challenge application limits in conventional isolation technologies. The CLB system realizes isolation of various structures from lightweight buildings to high rise /heavy structures by applying each device according to the function necessary for isolation. The CLB system develops extremely small coefficient of friction from 0.002 to 0.01, which realizes "period free" building. Many tests and inspections on the CLB have proved its performance stability, critical values and resistance, and the CLB is confirmed as a sufficient system to be put into application. The CLB made it possible to use a slender shape bearing, which was not recognized as a good application for restoration. As result, the system also contributes to provide longer period to buildings and expands the area of application. The authors plan to develop viscous damping devices (PSA & Gyro-Damper) along with the CLB to realize "an increase of damping capacity". These methods are considered to be extremely powerful tools from the perspective of response control. This report examined the theory and method of analysis of CLB with many useful examples of construction.

The Base isolation system has been considered as a technology to protect and ensure safety of human lives against large-scale earthquakes. However, with higher vision to prevent economic damages and ensure security for the future, authors strongly believe that base isolation is the technology that will realize the seismic protection concept for the next generation. We truly wish for further development and wide spread use of this technology.

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