

Comparison of Displacement Measurements in Exposed Type Column Base Using Piezoelectric Dynamic Sensors and Static Sensors

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Abstract: The Hyogo-ken Nanbu earthquake (Kobe earthquake) of January 17, 1995 caused extensive and severe damage to numerous Kobe city area buildings. After the earthquake, many steel structures were constructed using exposed-type column-base joints. Nevertheless, the capacity of these joints to absorb energy during earthquakes is small. For that reason, in the design of steel structures that use exposed-type column-base joints, it is believed that higher earthquake-resistant characteristics must be provided especially for joints of the first floor of a structure. Therefore, structural health monitoring is recommended. This paper presents the use of piezoelectric limit sensors to evaluate the resistance and displacement characteristics of exposed-type column-base using simple measurements.

Keywords: Smart Sensor, Health Monitoring, Exposed-Type Column Base, Anchor bolt, Deformed Bar

1. Introduction

In Japan, many structures currently made from steel frames using the pedestal construction method generally have an exposed type pedestal [1]. This construction method is used to join two structures using an anchor bolt embedded at CR of the first floor foundation, with the baseplate welded to the steel frame [2]. The exposed type column base is a steel frame with excellent construction compared with other building structures. However, to acquire high rotation rigidity by one side, we have a choice of numerous anchor bolts, and a measure, such as calling and enlarging a path. In the Southern Hyogo Prefecture Earthquake in 1995, much damage to exposed type pedestal of steel frame structure was observed [3]. Exposed type pedestals were recognized as weak points in steel frame exposed type column bases. To produce safer structures, reinforcement of those junctions of the first floor must be conducted of the characteristic with a great earthquake for resistance are special [4], [5], [6]. This study, using simple measurements, assesses the use of

piezoelectric limit sensors to evaluate the resistance and displacement characteristics of exposed-type column bases [7], [8].

2. Destruction of Exposed Type Column in Base Using Measurement Technology

2.1. Comparing Conventional and New Technologies

Measurement technologies, exemplified by the following systems, are used for quantitative evaluation of soundness aimed at disaster prevention and disaster reduction of a structure. Sensor systems currently used for displacement and oscillating measurements by static load measure displacement using a laser displacement meter or a contact type displacement meter [9], [10], [11]. Alternatively, characteristic vibration methods use slight movements of a vibration graph for analyses using finite element method or

other methods to identify characteristics such as destruction situations and stress concentration. This spectral ratio is called the amplification characteristic or a natural period by normalizing a horizontal vibration to perpendicular vibration in search of an H/V spectral ratio. A counting system that consists of a PC, a data logger, and a regular slight movement meter, requires approximately 1.5-2.5 million yen expense per measurement unit [4]. A laser Doppler velocity meter (LDV) irradiates a measured object with laser light. The velocity is detected from the phase difference by the Doppler effect of the illuminating radiation and catoptric light. This counting system, which consists of two LDV devices, a data logger, a PC, and a digital displacement meter, requires about 4.5-6 million yen expense per measurement unit [5].

A microelectromechanical systems (MEMS) application oscillating sensor system is a sensor in a single package. The three MEMS accelerometer axes and circumference circuit are of the electric capacity type. The MEMS is connected to the PC through a hub so that two or more sensor connections are possible. Regarding measurement of slight movements, searching for oscillation characteristics such as a particular frequency and the mode, can always be done from the measured acceleration data. Practical and convenient systems are extremely inexpensive, incorporating a PC, a hub, an NTP server, a GPS antenna, two or more vibration sensors, and

analytical equipment for a measurement unit: a system for structural monitoring might cost 3-4 million yen [6].

However, measurement by gauge or a Pi-gauge strain, or directly attached to several sensors for the measurement object, for fixing with bolt and nut. It is unsuitable for long-term monitoring. Determination of the safety and soundness at structural joints requires long-term monitoring during more than 20 years. However, no method exists that is related to smart sensing for which the measuring device and for which the risk of prediction to guarantee the duration of the required monitoring. First, confirm that you have the correct template for your paper size. This template has been tailored for output on the A4 paper size [12].

2.2. Outline of a Mounting Examination

Fig. 1 shows the form and the size of the examination object, which comprises square steel tube pillars of $300 \times 300 \times 16$ mm, a 38-mm-thick baseplate, and an anchor bolt of M27 presuming a pedestal part of inside low layer steel frame structure. It used premix type [Design intensity of 30 Ns/mm^2] concrete system uncontracted mortar for premix type, which shows the material strength of the steel materials that simulate the pedestal part of the steel frame structure being filled with mortar between anchor plates (50 mm), as presented in Table 1.

Table 1. Experiment material characteristics (*: Mill sheet).

Part	Performance	Yield strength (N/mm ²)	Tensile strength (N/mm ²)
RHS Column*	□300×300×16	358.0	474.0
Baseplate	PL-38	293.0	433.0
Anchor bolt	M27	309.1	432.9
Anchor plate	PL-36	285.5	440.2

2.3. Testing Method

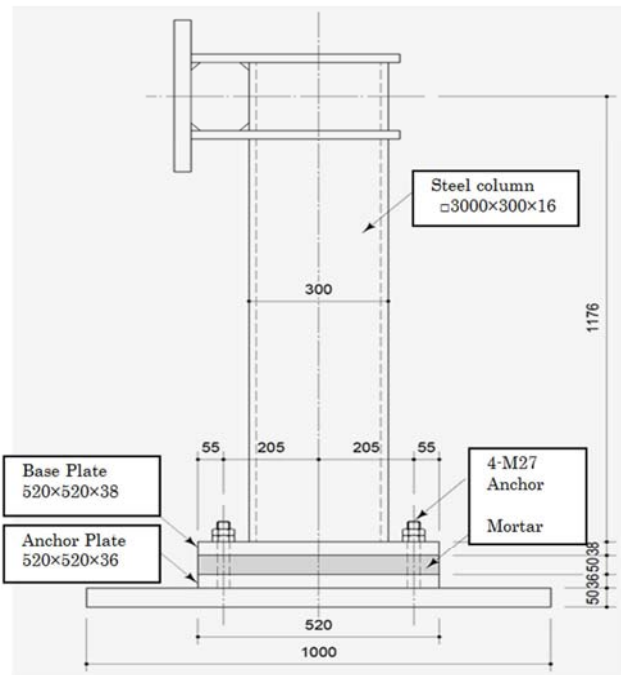


Figure 1. Test specimen layout.

Fig. 2 portrays the loading power equipment. Fig. 3 presents the displacement meter and measurement method.

The size and shape of a piezoelectric vibration sensor and a piezoelectric limit sensor are portrayed in Fig. 4. A high-tension anchor bolt fixes the plate of the examination structure to the mount. Horizontal loading power of 500([kN]) is supplied by a hydraulic press prepared for the examination. The apparatus simulates earthquake occurrence. Horizontal loading was applied three times, as shown in Table 2, with data based on top displacement. Load power No. 1 and No. 2 are loading power by the side of plus and minus equivalent to the modification limit value in cases corresponding to earthquakes affecting structures built according to standard building laws. Positive side load power No. 3 has a load with added triple transformation amount load of the transformable amount of load power, but with three times as much modification as No. 1 add 18 mm and assuming a strong earthquake. Details are presented in Table 2. The directions of the positive side and negative side of the pressurizing force are presented in Fig. 2. Load power was measured using a load cell attached to hydraulic jacks. The displacement positions measured using the displacement meter are depicted in Fig. 3. Apex displacement meter D_1 shows the horizontal displacement of the pressurizing force mind position.

Displacement meter P₁-P₄ shows the vertical direction displacement in the piezoelectric vibration sensor (dynamic load sensor) position of the baseplate top surface. Displacement meter B₁-B₄ senses the vertical displacement of the anchor bolt top. For comparative measurements, displacement sensor S₁-S₄ detects the displacement in the vertical direction in the jig that secures the piezoelectric limit sensor (static load sensor). It is noteworthy that the calculated value obtained by dividing displacement D₁ is obtained from the center position in which the top portion displacement sensor of the pressure force by the distance from the baseplate underside to load power center (1, 214 mm) and the deformation angle.

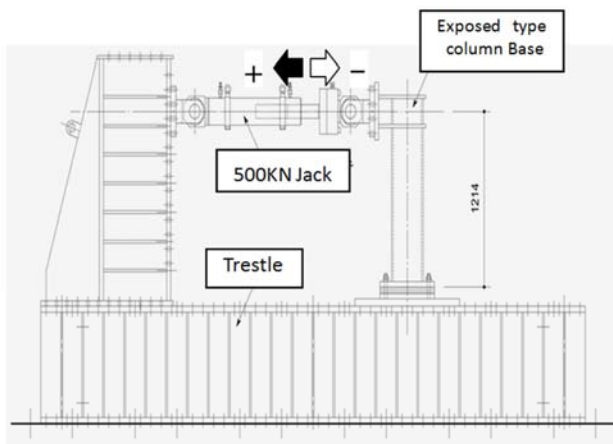


Figure 2. Load test apparatus.

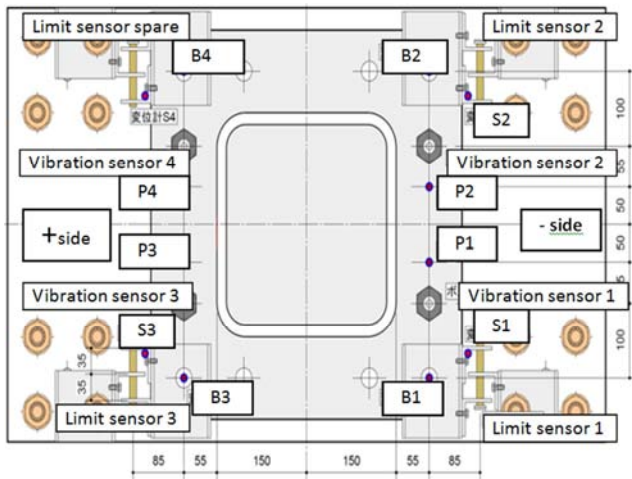
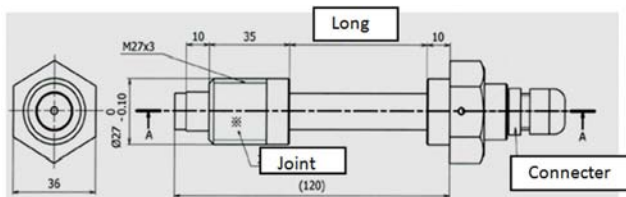
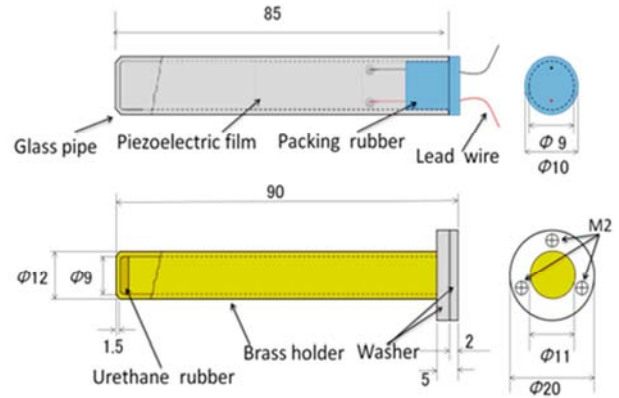


Figure 3. Sensors and measurement unit setup.



(a) Piezoelectric cable vibration sensor



(b) Piezoelectric limit sensor

Figure 4. Characteristics of piezoelectric sensors.

Table 2. Load pattern characteristics.

Load	Maximum displacement (mm)	Drift angle (rad)	Load direction
Load 1	6	1/200	+
Load 2	-6	-1/200	-
Load 3	18	1/67	+

For piezo cable vibration sensors V₁ and V₄, the head of the sensor is installed to be in contact with the baseplate top surface so that the tensile effect acts from small deformation to the sensor force. In addition, piezoelectric vibration sensors V₂ and V₃ are separated by a 1 mm gap between the lower surface of the baseplate top surface and the sensor head tensile force to the sensor. It is designed not to act at the time of small deformation. Additionally, four sets of piezoelectric limit sensors L₁-L₄ were installed for comparative measurements to measure the different static load (shown as spare sensor of Fig. 3), including one unit of the number of channels of a data logger unconnected not measured by restriction.

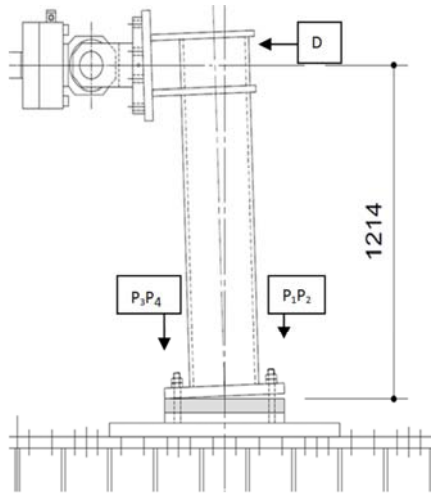
The load power and the measurement sampling frequency of displacement are considered for 1 s. Load measurement sampling frequencies for a piezoelectric vibration sensor, piezoelectric limit sensors, and the data sampling frequency are 1/100 s. As Fig. 4 (a) shows, after inserting piezoelectric vibration sensors (80 mm, AWG; Tokyo Sensor Co. Ltd.) in the center of urethane resin (φ15 mm × 135 mm) in the air, the piezoelectric cable sensor (sensor for dynamic load) conducted adhesion fixation, and made the outside tube type bolt form [13]. To connect the memory logger (LR8431; HIOKI E. E. Corp.) with a cable, the 2m-long φ4 mm lead was connected to the sensor for insulated processing. This sensor can measure the level of the voltage outputted according to modification of a piezoelectric vibration sensor by the system. It can measure the displacement and vibration by damage to the pedestal which faced this convenience.

Fig. 4 (b) shows the piezoelectric limit sensor (sensor for static load). The piezoelectric film (2-028 k/L, DT; Tokyo Sensor Co. Ltd.) was adhered in a hard glass pipe. A connector was made with a hole in a urethane stopper. This device was connected with an external cable after inserting a

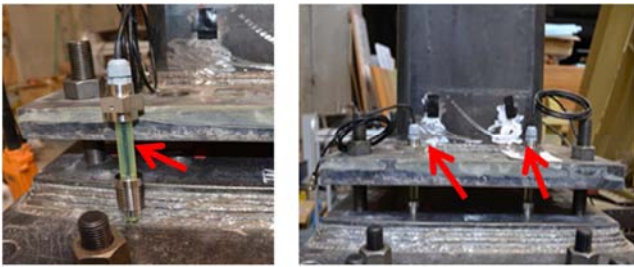
lead. To measure the structure object, an aluminum, brass, or iron holder can be used for the sensor exterior. Here, the brass exterior is damaged by crushing or shearing. The piezoelectric film of the sensor cannot be used because of that destruction. The piezoelectric film inside the glass tube is changed according to the loading power. The state of destruction changes the output voltage according to the measurement subject.

Fig. 5 shows the load power state of the test equipment in panel (a). If top displacement D_1 is forced by plus side load power, then P_1 and P_2 side will be pulled by right above lead, and will come floating. The moment which set the P_3 and P_4 side as the rotation center occurs.

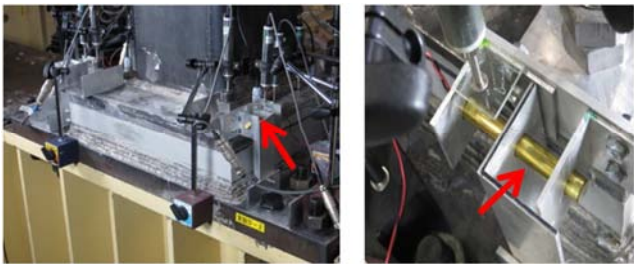
The measurement implementation situation of a piezoelectric vibration sensor is shown in panel (b). The attachment situation of a piezoelectric limit sensor and measurement metal fittings are shown in panel (c).



(a) Positive loading direction



(b) Setup of piezoelectric cable vibration sensor



(c) Setup of piezoelectric film sensors

Figure 5. Relation between displacement measurement and transformation by compressive stress.

3. Exposure Type Column Base Destruction Test of Result

3.1. Displacement Relation of the Baseplate Perpendicular Direction by Loading Power

Fig. 6(a) shows the relation between the load by the difference in the amount of top displacement and destruction time. For plus side load power level 1, 6 mm top displacement occurs. For minus side load power level 2, -6 mm top displacement occurs. For plus side load power level 3, 18 mm top displacement occurs. The measured load powers level 1 and level 2 do not progress to destruction. Measurements were interrupted before the limit of destruction to allow for measurement results of full destruction for load power level 3.

Fig. 6 (b) show loads of panel (b-1), panel (b-2) to the higher pressure load power level 1 (top displacement of 6 mm) and panel (b-3), panel (b-4) negative load power level 2 (top displacement amount of -6 mm). A relation is apparent between the output and the piezoelectric vibration sensor displacement. For the minus side load power level 2, the output of the piezoelectric cable vibration sensor was for top displacement of -6 mm panel (b-1), as shown in Fig. 6(b). Also, panel (b-2) for plus side load power level 1, the top displacement of plus side 6 mm is shown panel (b-3) with panel (b-4), the relation of displacement.

Fig. 6(b) shows, (b-1) presents the output of the oscillating sensor V_1 by the relation between displacement by load power and time. At 170 s, the maximum output voltage of 5 V was measured at many times of the maximum displacement.

In panel (b-2), the relation of V_2 is apparent when 170 s later the output of 5 [V] is measured as 0.45 mm maximum severe grade arises at the time of progress.

In panel (b-3) of output value of V_3 is the result of the measurement in loading power 2 by the side of the minus. When 100 s later measured maximum displacement 0.35 mm maximum output of 3.5 [V] is admitted.

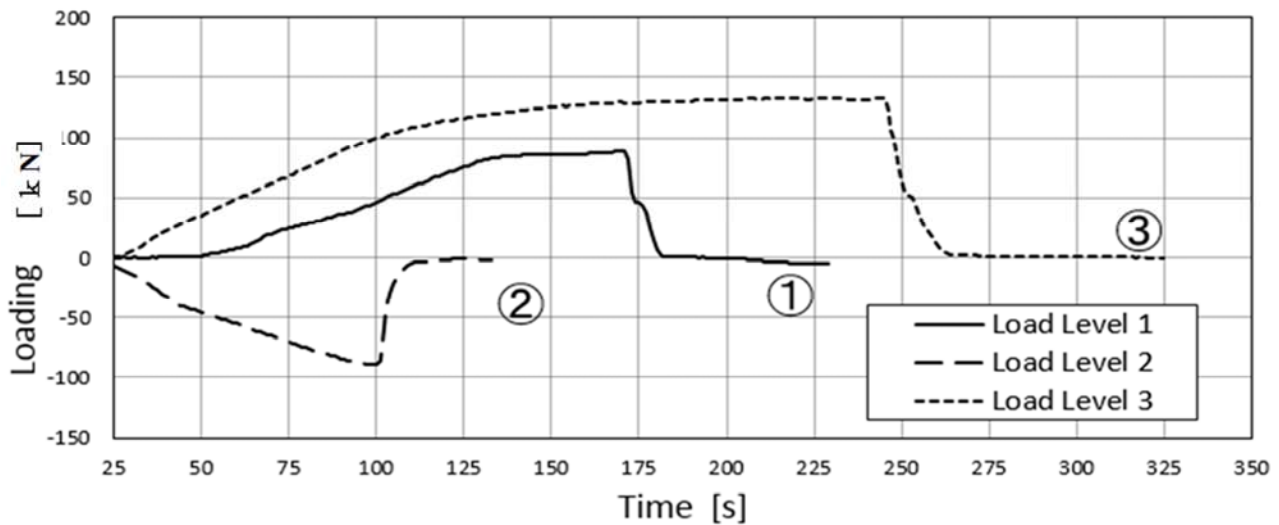
Panel (b-4) shows a similar measurement with output of V_4 load power No. 2 by the side of minus. At 100 s later, maximum displacement of -0.4 mm occurs with maximum voltage of 5 V.

Fig. 2 and Fig. 5 (a) show sensor output oriented in all directions. These figures show the relation with the displacement P_1 and P_2 , which is the load at the time of level loading power, and show the perpendicular direction on the upper surface of a baseplate. Right side load power level 3 is taken as the load which added the three times as much amount load (18 mm) of modification as the amount of modification of load power level 1, and assuming a strong earthquake. By the result of Fig. 6 (b) to the piezoelectric oscillating sensor V_1 , it is a maximum of about 1.4-mm (value added to actual measurement at 1 mm of throat depths) grade in load power level 1.

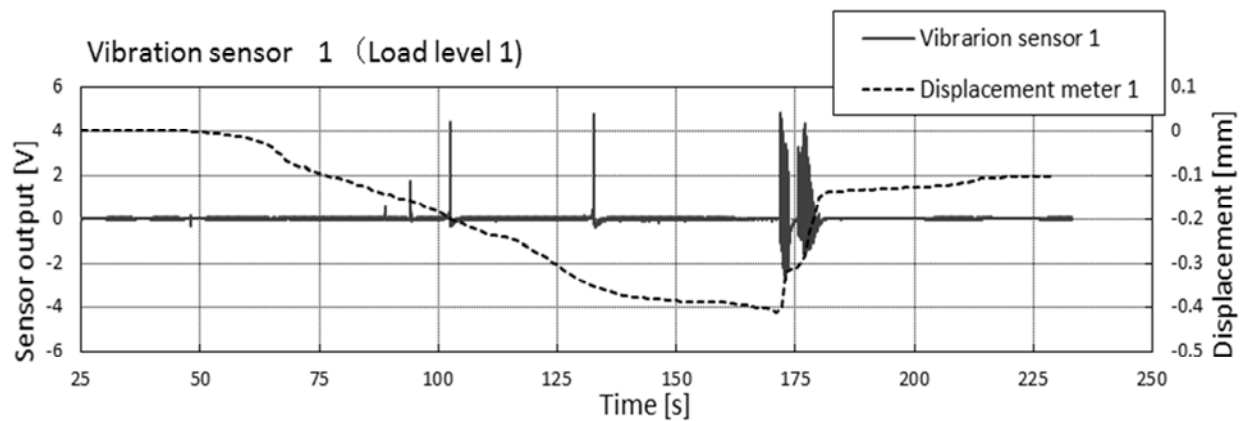
In loading power level 3, if loading power is calculated by the three times as many relative displacements in level 1,

then it will be assumed that the dilation distortion of a maximum of about 4.2 mm was forced. Large dilation is probably not forced from the relative displacement having been small in load power level 1-3 whose others are right

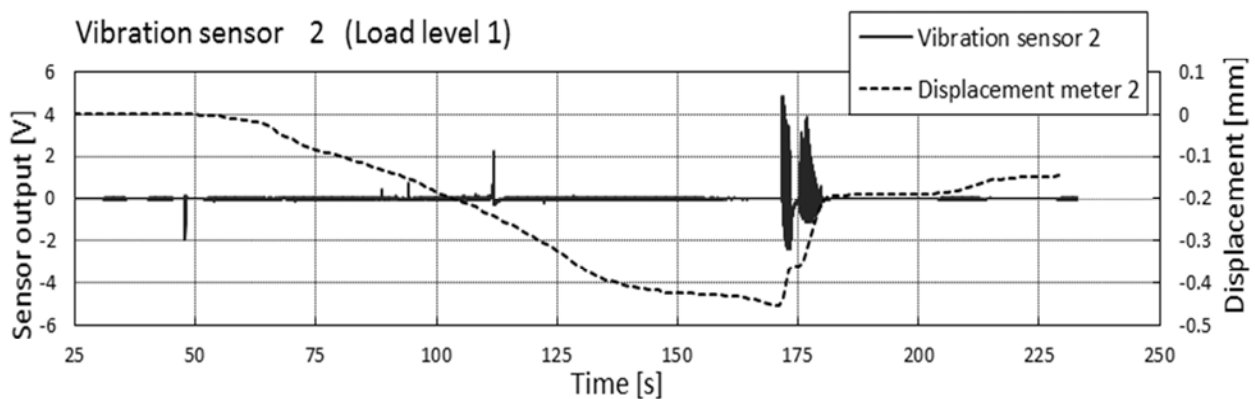
side loading power. Next, results obtained with piezoelectric vibration sensors V_1 and V_2 and piezoelectric limit sensors L_1 and L_2 are compared.



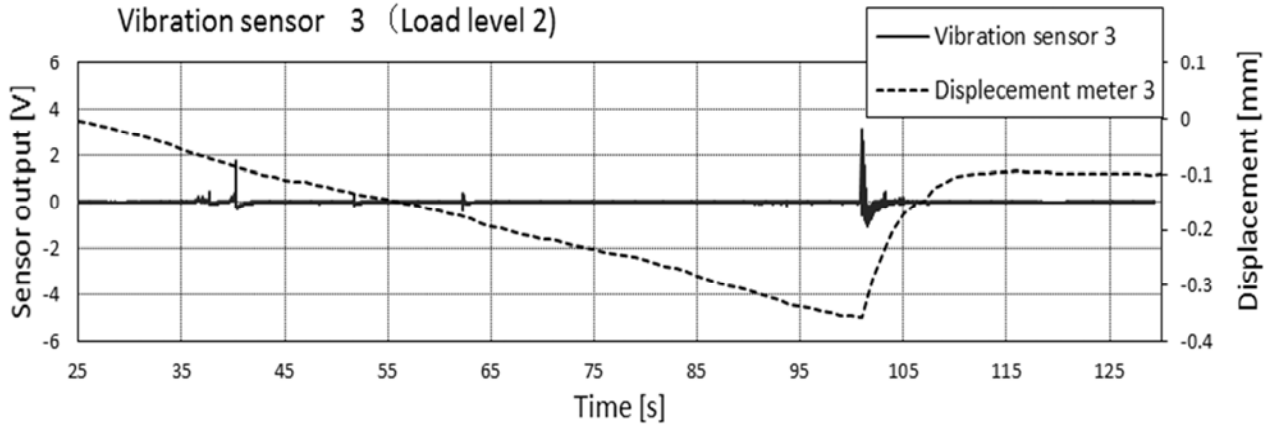
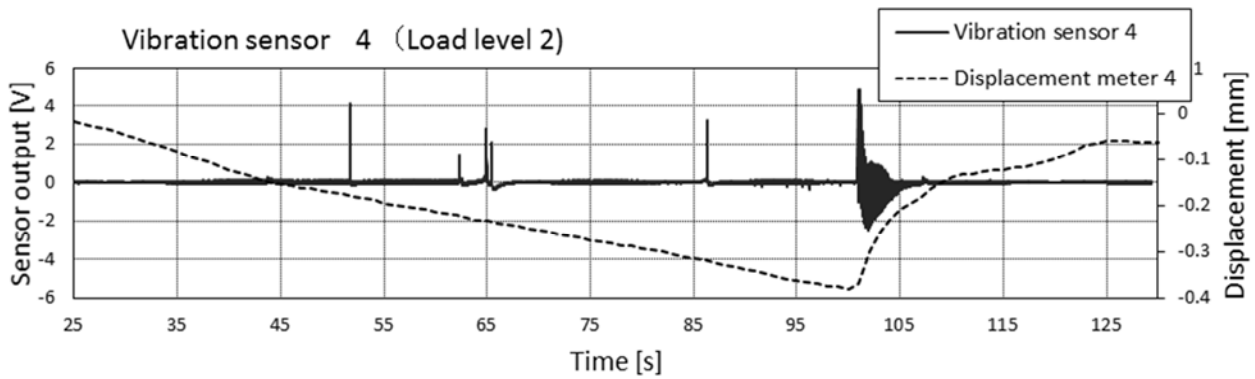
(a) Time history for each loading test (Load levels 1-3)



(b-1) Sensor V_1 (+Direction load)



(b-2) Sensor V_2 output (+Direction load)

(b-3) Sensor V_3 output (-Direction load)(b-4) Sensor V_4 output (-Direction load)

(b) Vibration sensor output No. 1 - No. 4 (Load levels 1, 2)

Figure 6. Time history for load and piezoelectric cable vibration sensors output (Direction load test level 1, 2).

3.2. Comparison of the Piezoelectric Vibration Sensor and Piezoelectric Limit Sensor.

A comparison of measurements obtained from piezoelectric vibration sensors V_1 and V_2 and piezoelectric limit sensors L_1 and L_2 in load power 1 is portrayed in Fig. 7 (a).

Panel (a-1) shows, that the maximum output voltage was 5 (V), when displacement was -0.4 mm. Panel (a-2) shows the same output voltage result for L_1 . Although the maximum relative displacement and -0.7 mm are measured, the output voltage of L_1 sensor is not measured because the piezoelectric limit sensor is designed to output only at the time of generating a large relative displacement by damage is found pedestal that. As the reason, by the capacity of load power level 1 spirit level, it was demonstrated reliably by lack of damage to the test piece. In panel (a-3), after about 170 s, output of 5.2 [V] was measured when displacement was -0.45 mm for the V_2 sensor output. For panel (a-4) conditions, displacement of maximum -0.5 mm was shown for the L_2 sensor output after 170 s. If this result is the same as that of panel (a-2), then no output is accepted.

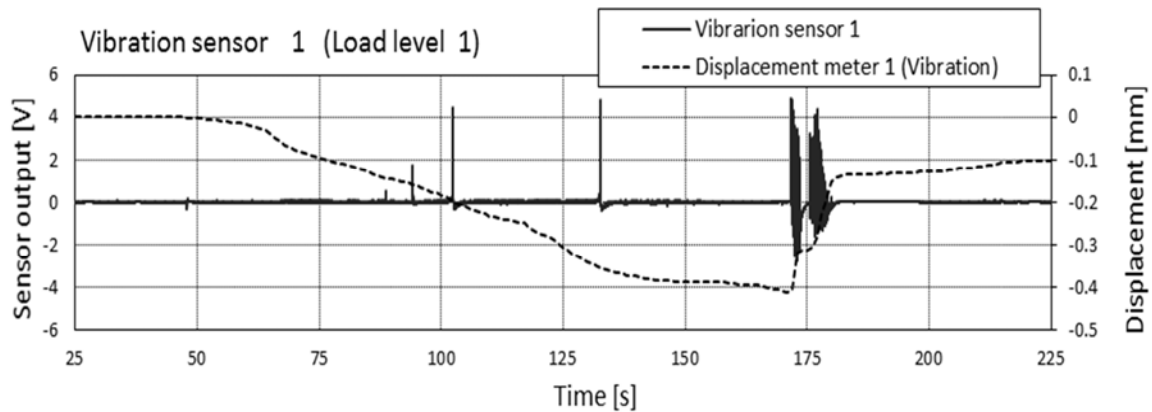
Fig. 7 (b) shows a comparison of the piezoelectric vibration sensors V_1 and V_2 , and the piezoelectric limit sensors L_1 and L_2 for load power level 3. At about 105 s

time was V_1 output of (b-1) shows displacement of -0.8 mm in the time of the output of 2.1 [V]. The maximum output judgment result is inferred from the maximum of the displacement meter reading. The displacement at this time was -5.5 mm. The output voltage of V_1 was 1.6 [V]. However, using this result alone, it is difficult to specify the relation between maximum output time and the maximum severity grade.

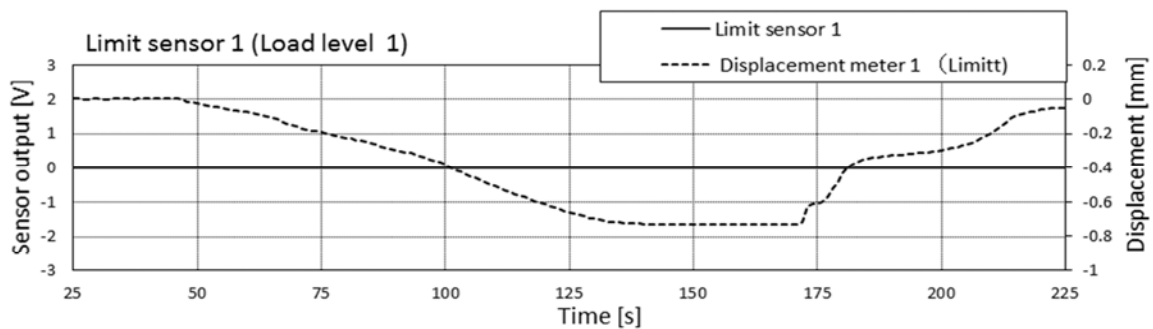
Panel (b-2) shows the measured L_1 output under identical conditions. As for the maximum displacement, the -4.5 to -5.8 mm numerical value was measured for about 175-210 s. As panel (b-1) shows, the maximum output voltage of V_1 sensor at the time of the 240-s progress, which was not observed with the L_1 sensor. Furthermore, in this spot, cannot recorded the maximum severe presuming a breakdown that 6.8 mm. As panel (b-3) shows, V_2 output voltage was 4.8 [V] representing relative displacement of -1.3 mm at the time of about 115-s progress. Furthermore, at the time of about 240-s, the output voltage of 1.7 [V] and the -5.8 (mm) of the maximum displacement were obtained. Panel (b-4) presents the same conditions, with measuring L_2 on the maximum output voltage. The maximum displacement measures -5.2 - +5.8 mm after about 190-210 s progress. Regarding the output voltage, maximum-2.2 [V] is measured. The S_1 of the

displacement gage in Fig. 3 and S_2 point compare the engine performance of both sensors. From pinpointing of the maximum distortion range, it was difficult to judge the relative displacement situation of from the nominal size of pump and lapsed time of a horsepower value by the piezoelectric vibration sensor for dynamic load measuring. However, the output voltage of the piezoelectric limit sensor for a dead load measuring shows the limits of the destruction point and the beginning of the destruction limit point during progress for 125 s. Furthermore, involvement is noted between the time in load power 1-3 of Fig. 6 (a) and the load.

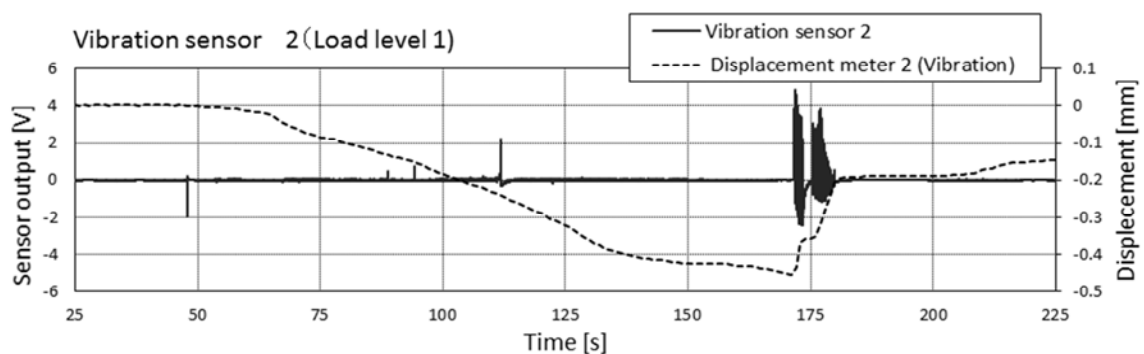
For load power level 1, the permissible capacity at maximum load is approximately 175 s, the load power level 2 maximum load is 100 s, and for load power level 3 at the measurement about 240 s. Consistent with that, the loading power instant of time of the maximum relative displacement which the piezoelectric vibration sensor, and a matching property are accepted. Regarding the loading power of a piezoelectric limit sensor, even when a judgment is difficult, the sensor for dynamic loads obtains the loading power also with the sensor for a dead load.



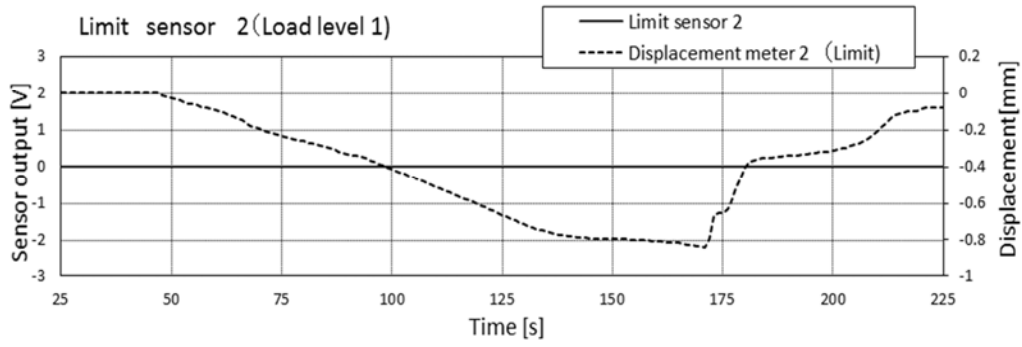
(a-1) Piezoelectric cable vibration sensor V_1 output voltage (Load level 1)



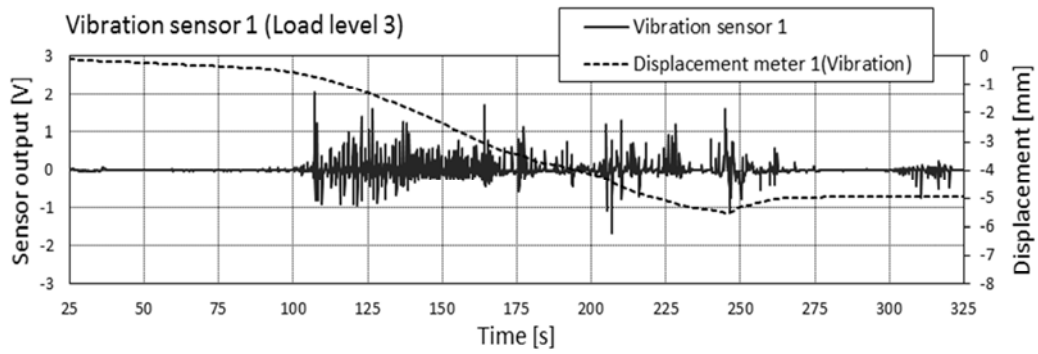
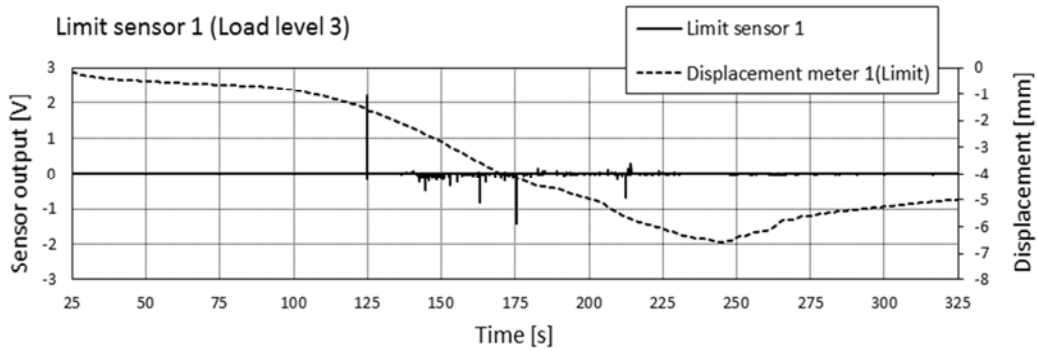
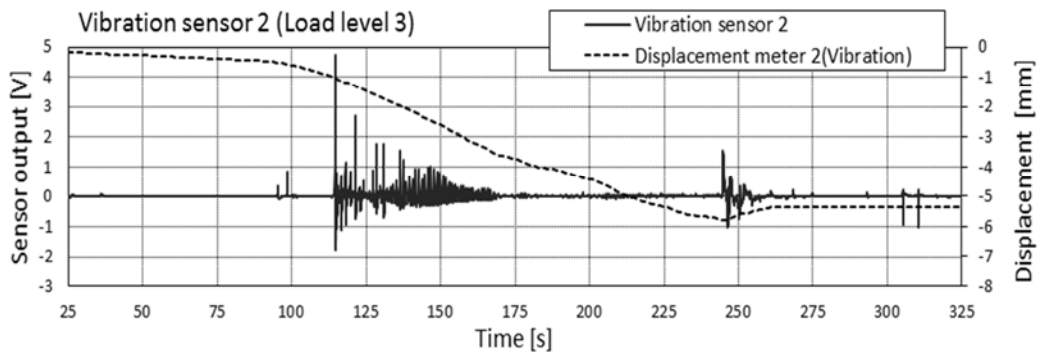
(a-2) Piezoelectric limit sensor L_1 output voltage (Load level 1)

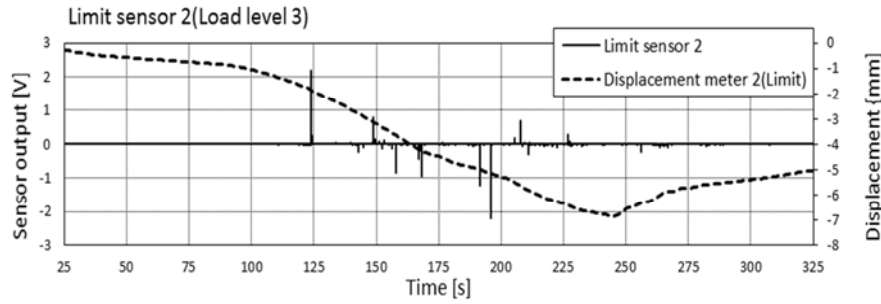


(a-3) Piezoelectric cable vibration sensor V_2 output voltage (Load level 1)

(a-4) Piezoelectric limit sensor L_2 output voltage (Load level 1)

(a) Piezoelectric cable vibration sensor and piezoelectric
Limit sensor output by load level 1

(b-1) Piezoelectric cable vibration sensor V_1 output voltage (Load level 3)(b-2) Piezoelectric limit sensor L_1 output voltage (Load level 3)(b-3) Piezoelectric cable vibration sensor V_2 output voltage (Load level 3)

(b-4) Piezoelectric limit sensor L_2 output voltage (Load level 3)

(b) Piezoelectric cable vibration sensor and piezoelectric limit sensor output by level 3 load

Figure 7. Relation between piezoelectric cable vibration sensor output, limit sensors output and displacement.

4. Simulation of Destruction in Exposed Column Bases

4.1. Relative-Displacement Calculation of a Baseplate with Perpendicular Loading

The distortion angle R of a pillar is sought using the following equation for the architecture presented in Fig. 8.

For the top of the baseplate of rotor displacement δ_θ , the sum of the bending deformation of column top of displacement δ_c divided by the distance from the baseplate under the surface to force at 1214 mm [14], [15].

$$R = \delta_\theta + \delta_c / 1214 \quad (1)$$

Deformation angle R is a structural safety assessment value: weak and normal earthquakes have $R \leq 1 / 200$ rad; a strong earthquake generally has $R \leq 1 / 75$ rad.

Experiment specimens are designed as presented above.

Top displacement δ_c is produced by deformation, bending, and lateral force. P is the length of the columns from the baseplate surface to loading location: $1214 - 38 = 1176$ [mm]. The beam cross-section can be found using eq. (2) with secondary moment I and steel Young's modulus E [12] [13].

$$\delta_c = P \times 1176^2 / 3EI \quad (2)$$

However, the percentage of apical displacement δ_c caused by bending deformation of column deformation angle R can differ with various conditions: beam column cross-section size, number and length of anchor bolts, etc.

Therefore, it cannot categorically be said how, in this experiment, the deformation angle R gas ratio is about 20%. Rotation angle θ of the baseplate and the deformation angle R accord with eq. (3) [12] [13].

$$\theta = 0.8R \quad (3)$$

The displacement of S_1 to δ_{S1} is displacement measured from the rotation angle θ of the baseplate and pivot distance 410 mm, calculated from formula (4) below.

$$\delta_{S1} = \theta \times 410 = 0.8R \times 410 \quad (4)$$

Displacement S_1 of δ_{S1} expected from weak and

medium-class earthquake disasters are presented in Table 3.

4.2. Result of Simulation

Actual measurements and calculated values were compared. Results of Fig. 6 and Fig. 7 show that measurement loading power No. 1 + direction displacement is 0.35 mm, loading power No. 2 - direction displacement of measurement is averaging about 0.31 mm.

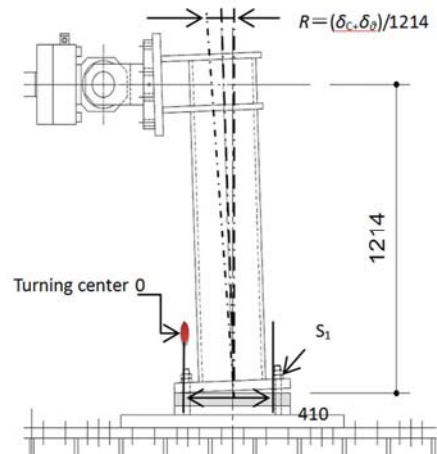
Considered for this example specimen was had + direction a gap of 1 mm during in the designing, for reason that measurement of displacement is causing was 1.28 mm by in the loading power No. 1 of + direction.

In addition, values of piezoelectric vibration sensors for loading power No. 3 + direction showed average displacement of 5.56 mm. Values of cable piezoelectric limit sensors indicated average displacement of 4.85-5.8 mm.

Furthermore, this sensor can measure the final state as the beginning of destruction from the sensor output decision feasible. Figs. 7 (b-2) and 7 (b-4) show that suggested partial destruction occurs because of displacement of approximately 1.5-1.8 mm or more.

Table 3. Target displacement for testing comparison.

	Drift angle R	Displacement δ_{S1}
Medium Earthquake	1/200 rad	1.6 mm
Strong Earthquake	1/75 rad	4.4 mm

**Figure 8.** Column base composition experiment.

5. Conclusion

We proposed a simple measurement system for displacement using in exposed-type column-base structure static load measurement using a piezoelectric limit sensor and dynamic load measurement with a piezoelectric vibration sensor. The load power for displacement sensors and other sensors were related to static loading power. The following findings were obtained.

Conventional experimentation methods show difficulty measuring exposed-type column-base data from immediately before the beginning of destruction to final destruction. However, the piezoelectric limit sensor output obtained using this measurement system was verified through experimentation. This experimental measurement method uses a piezoelectric limit sensor and mounting bracket to monitor the health of an exposed-type column-base structure. Results show that the degree of damage to a structure can be inferred from the sensor output. Though it is difficult to speculate on the structural damage initially, or at the level of final failure from output values of piezoelectric vibration sensors used to measure the dynamic load. In the simulation effect, final displacement in the base surface of the exposed-type column bases calculations are compared with measured values in somewhat smaller numbers.

However, the displacement sensor limits the sensor piezoelectric output point to precisely calculated measured values. This simple displacement measurement system used for a static load is less than 1/20 the cost of gauges and laser displacement sensors that are conventionally used for measurements. This system can quantify structural deformation that affects the long-term health of structures, and allow monitoring of static loads and earthquake damage. Furthermore, its use in many areas can improve the system reliability. Damaged buildings and exposed steel column bases can be repaired and retrofitted to provide better safety and strength.

Acknowledgements

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