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Evaluation of Tsunami Loading Based on Collapse Load of Structures

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ABSTRACT: The hydraulic test and the static loading test is carried out on the 1/20 scaled reinforced concrete standing wall specimens in order to evaluate the nonlinear response of the structure under the wave load. The different overturning moment strength is given by the position of the tensile rebar, while the specimen has identical shape. The strong specimen shows elastic response, and the weak specimen overturned by the identical tsunami wave load. The standard specimen deformed, but restore its original position after the yielding of the tensile rebar. The maximum overturning moment by lateral wave pressure increases in proportion to the water height in front of the specimen, but saturates at a certain water level. The impulsive moment act on the specimens at the first contact, but the tensile rebar does not response to this impulsive force. The experienced maximum response evaluated by the cross point of static loading hysteresis in between damaged and non-damaged standard specimens. The discrepancy exists between the cross point and the overturning moment evaluated by the lateral wave pressure in the hydraulic test. It caused by the buoyant forces at the bottom, and the difference can be explained by the estimate in calculation.

1 INTRODUCTION

A number of the buildings including reinforced concrete structures and steel structures are washed out by Tsunamis on 2011 Great East Japan Earthquake. The maximum inundation depth of Tsunami exceeded 10 m on heavily damaged area in Tohoku district. The Japanese government settled building code for tsunami shelter after this earthquake, where 1.5 ~ 3.0 time water height of hydrostatic force is proposed as the design tsunami load with safety margin. This design load was derived from the maximum value of the wave load database in past hydraulic tests including super critical flow, while lateral loading carrying capacity of collapsed or overturned reinforced concrete structures is generally smaller than hydrostatic forces of observed inundation depth in post-earthquake damage observation on 2011 Great East Japan Earthquake. The required base shear for 5m tsunami exceeds general seismic demands in Japanese Building Code for small buildings, and local government cannot deal with tsunami hazards by effective utilization of retrofitted or existing buildings structures. Therefore, the practical tsunami load effective to the building collapse is desired from domestic structural engineers. The following items can be proposed as a significant difference between seismic and tsunami load: (a) load distribution, (b) loading duration and (c) buoyant force. It is difficult to estimate the effect of those parameters on collapse mechanism of the structures only by post damage observation. In addition, past hydraulic tests was carried out for measuring wave pressure or load on massive seaward obstacles, and the collapse load of the building structure by Tsunami was not evaluated by the test. In this study, hydraulic and static loading test are carried out on 1/20 scaled reinforced concrete structures, in order to compare the collapse load and response under loading.

2 TEST PLAN

2.1 Specimen

Hydraulic test and static loading tests are carried out on three types and six reinforced concrete specimens, where all of the specimen has identical outer shape: 700mm height, 800mm width, and 120mm depth hollow concrete walls without openings. The plan and elevation of the specimen are shown in Figure.1. ϕ 2 rebar and concrete mortar are used for the specimens. The specimen is designed to fall down by the fracture of the two tensile rebar, which simulate the pile reinforcement of overturned buildings by Tsunami. The concrete was casting on the 12 mm base steel plate. The specimen fixed on the base plate with two tensile side rebar and six compression side rebar. Each rebar penetrate the plate and anchored by weld on the back side to make enough yield deformation in the hydraulic test.

Only position of tensile rebar is shifted among three types of specimens: standard specimen, strong specimen, and weak specimen, so that the overturning moment strength changes without changing applied wave load. The distance from tensile rebar to compressed concrete edge is 60 mm for standard specimen, 110 mm for strong specimen, and 35 mm for weak specimen. The thickness of the outer wall and bottom is 20mm, and hollow section of the specimens reduce the contribution of the self-weight on the overturning moment strength as well as the actual building. The rebar reinforced in single layer at 50 mm intervals on wall. 12 mm timber mold left inside of the concrete walls in order to prevent concrete cracks by impulsive wave pressure.

The result of material test shows in Table.1. Ultimate strength of the concrete mortar is 36.4 N/mm^2. Tensile strength of the rebar is 656 N/mm^2 and higher than normal deformed bar, while the stress strain relationship shows obvious yielding point as shown in Figure.2. Elastic modulus of rebar is 1.9×10^5 N/mm^2 and yielded with about 5000 μ strain. The strain hardening effect after yielding is not so obvious in this material.

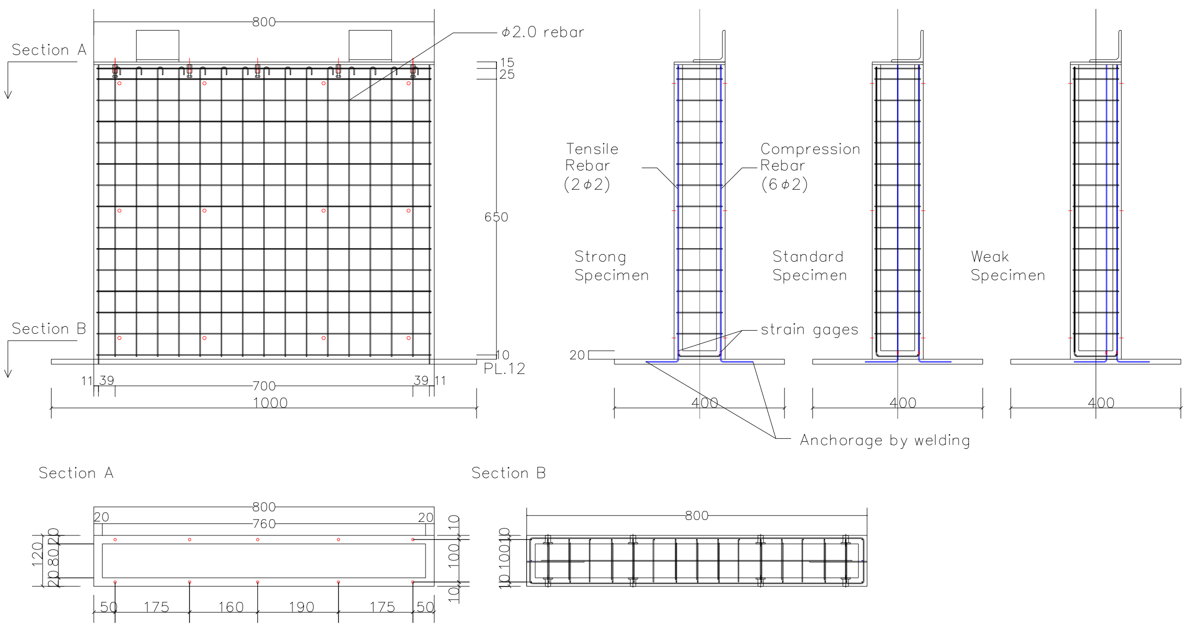

Figure 1. Plan and elevation of the specimens.

Table 1. Material property of the specimen

Mortar	Compressive Strength (N/mm^2)			
	36.4			
Rebar ϕ2	Yielding Stress (N/mm^2)	Maximum Stress (N/mm^2)	Maximum Strength (kN)	Young Modulus (kN/mm^2)
	656	712	2.24	189

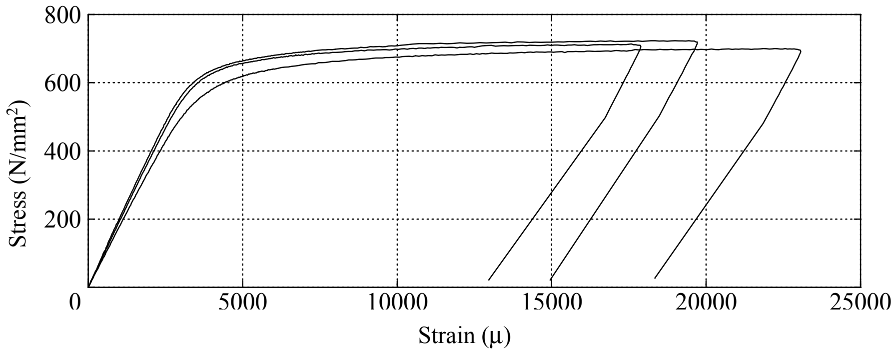

Figure 2. Material test of the rebar

2.2 **Measurement in Hydraulic Test**

The Hydraulic test was carried out with wide deep hybrid flume in PARIS. Section of the flume shows in Figure.3. Specimens are placed on 2.5m far from 1.5m upright revetment concrete wall without protection wall or slope. Induced wave is soliton wave, and the maximum wave height is 0.5 m in the offshore part. The water height, pressure, velocity in front of the specimen was measured in the test. 15 mm acryl plate fixed on both side of the concrete panels in order to embed the wave pressure gages. Total weight of the specimen including this acryl plate is 97 kg (without base plate). The height of the lowest water pressure gage is 70 mm, and five gages distributed at 140 mm intervals in vertical direction. The lateral drift of the specimen is derived from the acceleration meter, which located inside of the hollow concrete on top and bottom. The strain gages are attached on tensile and compressive rebar.

The wave height without the object is measured before the test. The inundation depth and Froude number on site are 0.202 m and 2.15. Firstly, the specimen fixed by rear steel braces was tested in order to evaluate the wave load on rigid body. After removing the braces, the nonlinear response of the specimen under wave load was tested. When the specimen survived in the hydraulic test, the load-displacement relation was evaluated by the static loading test after the hydraulic test. Static loading test was carried out with loading jacks in Earthquake Research Institute. The lateral load is given at two-thirds height of the specimen, which is compatible with equivalent single degree of freedom system in seismic loading. The lateral drift is measured on the top of the specimen until tensile rebar is ruptured.

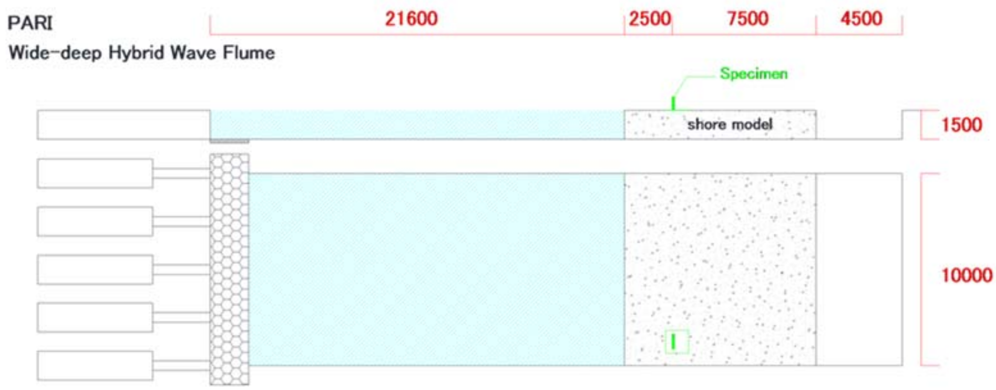

Figure 3. Plan and elevation of the hydro test flume

2.3 **Calculation of the Moment Strength**

The moment strength of the specimen is evaluated with the summation of tensile rebar resistant, self-weight, and buoyant force as shown in formula (1). The contribution of compression rebar is ignored in calculation. Because the wave pressure distribution in vertical direction is not obvious in past research, the buoyant force is treated as a water weight of the submerged concrete volume in front of the specimen. The moment strength decreases in proportion to the front water height because of the buoyant forces. The overturning moment is derived from hydrostatic force of water height in front of the specimen for soliton wave as shown in formula (2). The past research proposed hydrostatic force of 3.0 times water height on free field as the empirical maximum wave load for run-up tsunami on land. The strength of the specimen and the hydrostatic moment of the water height are compared in the Figure.4. The wave load exceeds the strength of standard and weak specimens in calculation, while the strong specimen has enough high strength rather than the wave load.

$$M_u = \sum (0.9 a_t \sigma_y \times D_1) + (W - \rho g V) \times D_2 \qquad (1)$$

$$M = \int_0^H (B\rho g (h_w - z) z)\, dz \qquad (2)$$

where, a_t: section of tensile rebar, σ_y: yielding stress of rebar, D_1: distance from the position of tensile rebar to the rotation center, W: total weight of the specimen, ρ: density of water, g: gravity acceleration, V: submerged volume of the specimen, D2: distance from the gravity center to the rotation center, H: the minimum value between water height in front of the specimen (h_w) and height of the specimen, B: width of the specimen

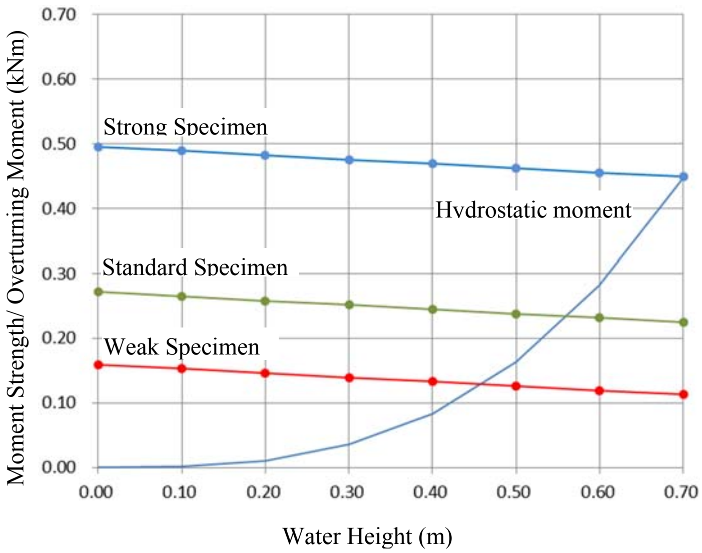

Figure 4. Water height that gives equivalent hydrostatic forces with the strength of the specimen

3 EXPERIMENT RESULT

3.1 The behaviour of the specimens

The behaviour of the specimens in hydraulic test is shown in Figure.5. The wave overflows the specimen due to the afflux. The strong specimen shows elastic slight deformation by the Tsunami and the residual deformation or cracks is not obvious after the test. On the other hand, tensile reinforcing rebar yielded and ruptured in the weak specimen. The specimen moved and lied in 0.3m back from the original position. As for the standard specimens, the rotating deformation due to the yielding of the tensile rebar is observed at the maximum water height, but the specimen restored in its original state according to the reduction of the water height. The specimen shows no obvious residual inclination angle, but residual cracks between bottom concrete and the base plate after the test. The correlation between moment strength and damage of the specimens is appeared clearly in this hydraulic test.

(a) Strong Specimen (b) Standard Specimen (c) Weak Specimen

Figure.5 Behaviour of the specimens in hydraulic test

3.2 Time history response of the specimens

Figure.6 shows time history of the overturning moment by the wave load, the water height in front of the specimen and the strain of tensile rebar.

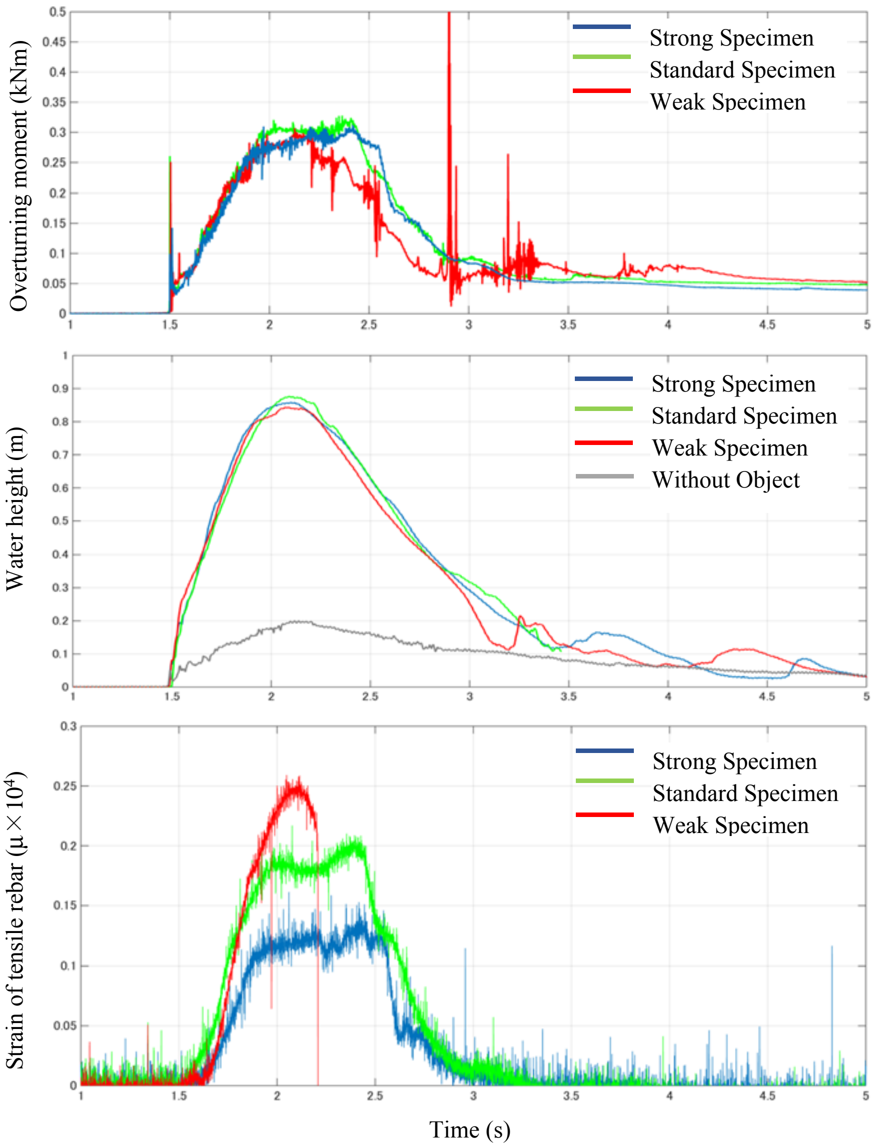

Figure.6 Time history response of the specimens in the hydraulic test

The overturning moment is derived from the integration of the measured wave pressure. The maximum water height is about 0.85 m irrelevant to the behaviour of the specimens, and the overturning moment also shows identical value in all the test. The maximum values for those are recorded at the same time, and the time duration is about 2 seconds, which is enough long for the nonlinear deformation of the reinforced concrete structures. The impulsive forces acts on the specimen in extremely short period at the first contact, and the peak value is close to the maximum overturning moment. The strain of tensile rebar increases according to the overturning moment, while the value dose not response to this impulsive forces. The maximum recorded strain is smaller than yielding strain in the material test.

3.3 Hysteretic relation between water height and overturning moment

Figure.7 shows the relation between the overturning moment and the water height in front of the specimen. The overturning moment derived from the measured water height with the idealized hydrostatic water pressure distribution is compared in the figure. Two overturning moment evaluated by water height and pressure gages are similar up to a certain water height. The slope of the overturning moment to the water height turn to be smaller than expected when the water height exceeds 0.60 m. This water height is consistent with the empirical upper bound wave load in the past research. The effects of the overflowing or behaviour of the specimen on the reduction of the overturning moment is negligible. For soliton wave, the collapse of the building can be prevented if the building has enough strength rather than saturated upper bound wave force, while the water height increases according to the velocity of the tsunami.

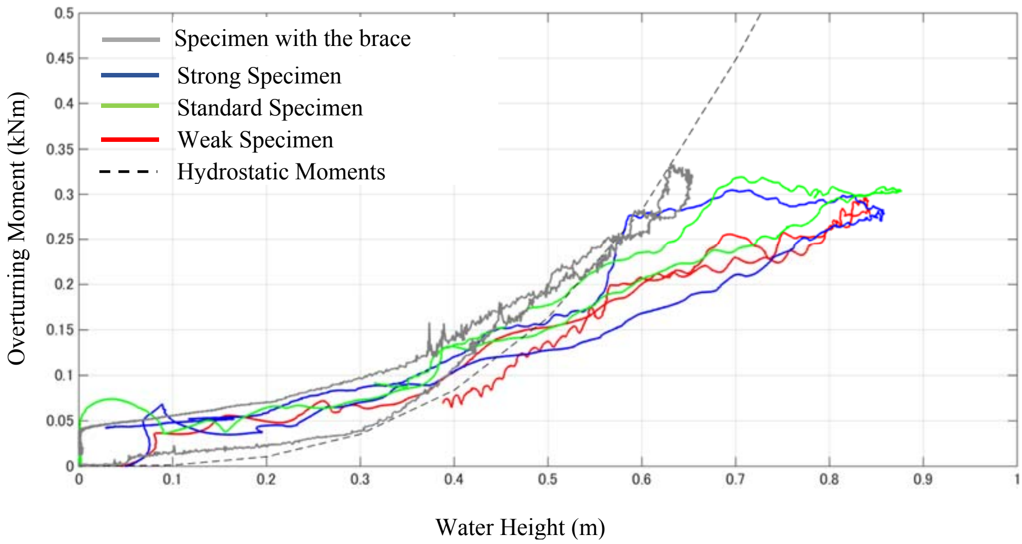

Figure.7 Relation between overturning moment and water height in the hydraulic test

3.4 Wave pressure distribution

Figure.8 shows the vertical distribution of the maximum wave pressure and wave pressure at the maximum overturning moment. The hydrostatic wave pressure distribution derived from the maximum water height is compared in the figure. The water pressure at the maximum overturning moments shows typical triangle distribution as well as the hydrostatic, although the measured water pressure is almost half of the value expected from the water height. The maximum wave pressure is almost same with the wave pressure at the maximum overturning moment in the higher measuring points, while the maximum wave pressure shows obviously higher value due to the impulsive first contact of the tsunami in the lower measuring points.

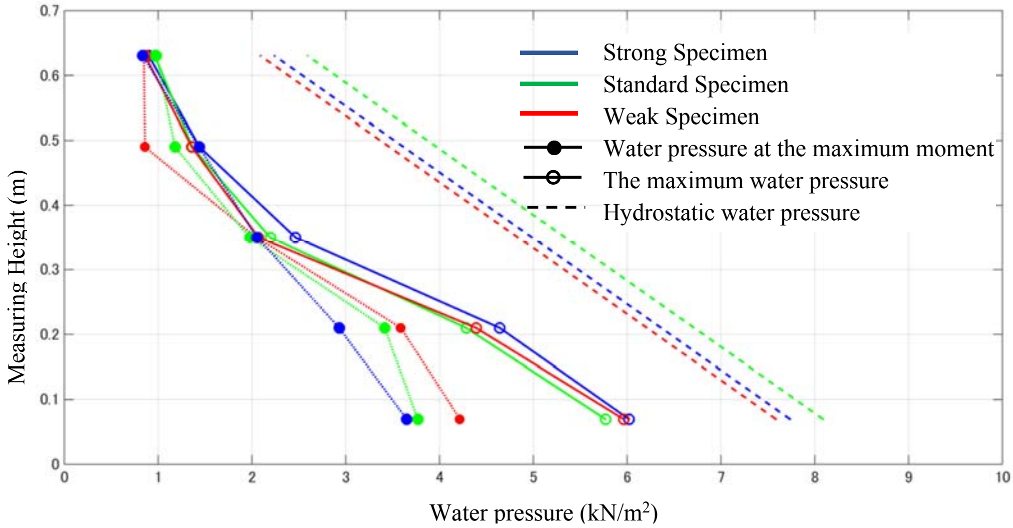

Figure.8 Water pressure distribution in vertical direction

3.5 Comparison between hydraulic test and static loading test

Figure.9 shows hysteretic relation between the lateral drift and overturning moment in the test. The static test was also carried out to the standard and strong specimens after the hydraulic test in order to evaluate the experienced maximum response point by comparison of the hysteresis between damaged and no damage specimens utilizing the peak-oriented characteristic of reinforced concrete. The maximum moment strength of the strong specimen is 0.50 kNm, which exceeded the maximum overturning moment 0.30 kNm in the hydraulic test. On the other hand, the strength of the weak specimen is only 0.25 kNm, which is slightly smaller than the overturning moment in the hydraulic test, although the specimen immediately falls down with fracture of the rebar. For the standard specimen, the overturning moment in the hydraulic test is smaller than the maximum strength or the experienced maximum restoring force of the specimen, while the yielding of the tensile rebar is observed in the test. The difference between those moments is about 0.035 kNm, and it may cause by the buoyant forces at the bottom. This value can be explained by an estimate of the buoyant moment as an integration of the uniform buoyant wave pressure on the bottom surface of the specimen, when vertical and lateral wave pressure are continuous at the bottom.

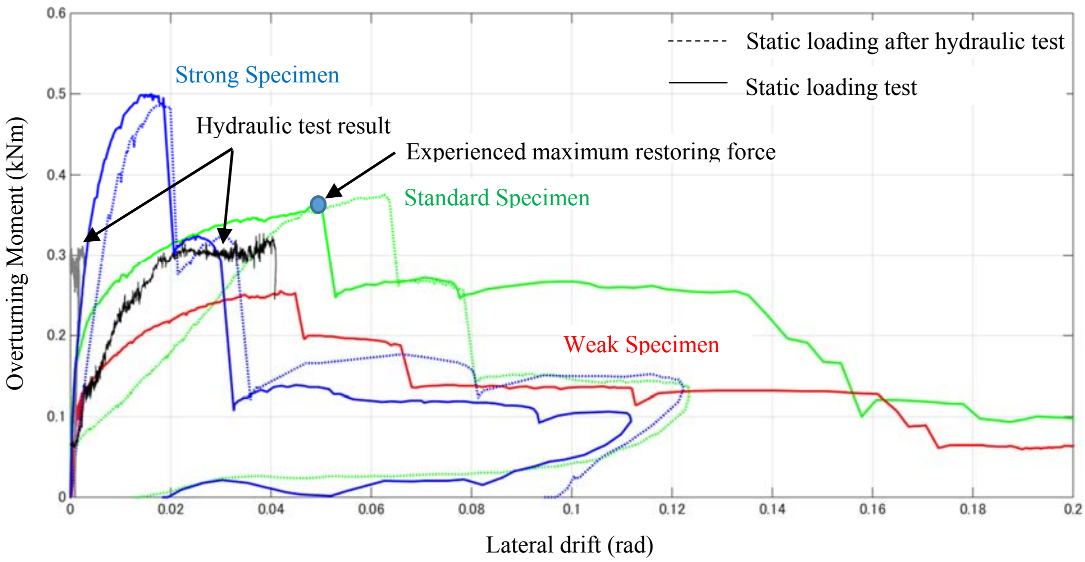

Figure.9 Load-displacement relation of the specimens

4 CONCLUDING REMARKS

The study shows the nonlinear response of the reinforced concrete wall specimens in hydraulic test and static loading test. The following conclusions may be drawn from these test results:

- The response of the specimens under identical wave loads changed by the moment strength. The weak specimen fall down, the standard specimen inclined by the yielding of rebar and the strong specimen shows elastic response in the hydrauric test.
- The water height in front of the specimen exceeded four times of the water height without the object. The overturning moment can be geneally explained by the hydrostatic force of the water height, but saturates from a certain water level.
- The time history of the overturning moment or the strain of the tensile rebar was not influenced by the response of the specimens. The impulsive forces acted on the specimen at the first contact, but this force was not effective to the strain of the tensile rebar.
- The discrepancy exists bettween the experimenced maximum restoring force and the overturninig moment evaluated by lateral wave puressure. The overturning moment increases due to the buoyant forces at the bottom of the specimen in the hydrauric test.

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