Bi-directional Loading Test of Reinforced Concrete Walls Used in Box Culverts

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ABSTRACT

The object of the present paper is to investigate the mechanical property of reinforced concrete walls in three dimensions. Emphasis is placed especially on squat walls without side columns because this should be applicable to seismic performance verification of box culverts. For this purpose, loading test of horizontal bi-direction under constant vertical load was conducted. Based on the test results and additional numerical analysis, characteristic of limit deformation of wall in horizontal plane, combination effect of wall and frame and effect of cyclic loading on deformation performance are developed.

INTRODUCTION

Nonlinear mechanical property of reinforced concrete members in two dimensions has been extensively studied by many researches. Then upgrading of seismic safety assessment system on underground structures in nuclear power stations has been advanced so far[1][2]. The system has indeed contributed to streamline design practice on two dimensional structures such as ducts and waterways that have the same section in the longitudinal direction. However, the application to three dimensional structures was dealt with as a future subject. Here, three dimensional structures can be found, for example, pump room with walls orthogonal to water flow direction, curve of waterways and section changing part which represents in the connection between waterways and pump room. Although dynamic analysis based on finite element model plays a key role to estimate three-dimensional seismic response, it is essential to reduce the structure model with degrees of freedoms in accordance with that of periphery ground. Therefore, understanding of mechanical property in a macroscopic level of wall member is important. For this purpose, loading test for single walls and simple assemblage of walls was conducted and three dimensional mechanical properties of them were investigated.

Concerning bi-directional test of walls, Katsumata et al.[3] presented a precedent study, where seismic wall with side columns was focused and the following results were derived: (a) Deformation to out-of-plane direction does not influence on in-plane maximum load, but deformation to in-plane direction reduces out-of-plane maximum load. (b) Deformation to out-of-plane direction reduces ductility to in-plane direction. These characteristics are reconsidered for our target structures.

TEST PROGRAM

Outline

Reinforced concrete wall specimens were loaded toward the fixed direction in horizontal plane under constant vertical load. Horizontal loading was controlled by displacement and continued until the specimen became unable to support the vertical load. Hereafter, directions X, Y and Z are defined as shown in Fig.1. Since we assumed that walls deform as a member of box culvert, the rotation of upper and lower edges around X axis was restricted. This test has seven cases, which include six single wall cases and one wall-frame complex case. Test parameters were loading direction in horizontal plane and the difference of monotonic or cyclic loading.

Specimen

The size of single wall specimen was 1,200mm in width, 90mm in thickness and 700mm in height and loading stabs were attached up and down as shown in Fig.2. Though the actual wall as a member of box culvert is a little squatter, the aspect ratio became to 12:7 due to the limitation of loading apparatus. Fig.3 illustrates rebar arrangement. The ratio of two layers of vertical rebars to the area of concrete was 0.89% and that of horizontal rebars was 0.90%. Vertical rebars were welded to the steel plates that were added on the top and bottom surface of the specimen. Horizontal rebars were anchored with 180 degrees hook in the end. Wall-frame complex has the shape of the above-mentioned wall united with three-span frame. The amount of vertical rebars by unit length in the frame part was almost the same with the wall part, but that of horizontal rebars was half of the wall part.

Concrete was mixed aiming at the compressive strength of 30N/mm^2. Normal portland cement as matrix, crushed stone with maximum size of 13mm as coarse aggregate were used, respectively. In material test after hardening the performance as Table.1 was obtained and from tension test of D6 bars (deformed bar with nominal diameter of 6.35mm and nominal area of 31.67mm^2), yield strength of 382 N/mm^2 and maximum strength of 534 N/mm^2 were obtained.

The flexural strength calculated by section analysis and the shear strength derived from practical estimation methods

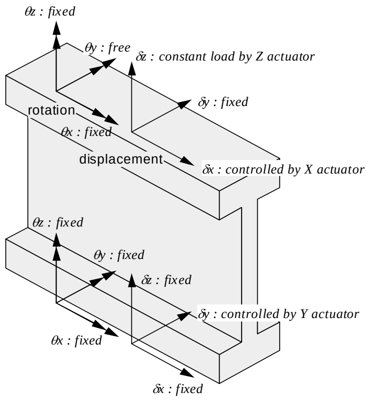
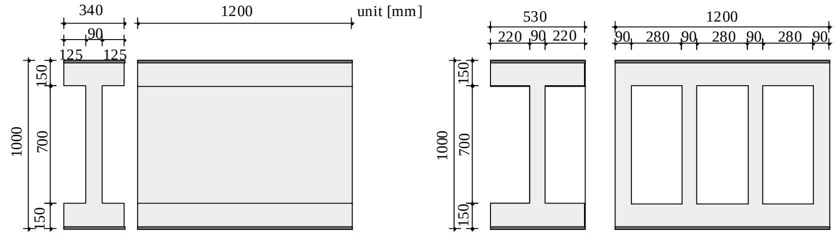
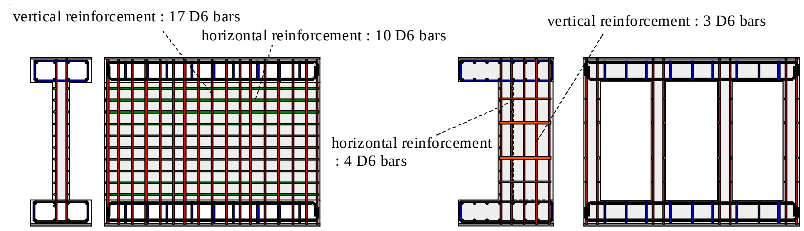


Fig.1 Boundary Condition of Test



(a) single wall (b) wall-frame complex

Fig.2 Shape and Size of Specimen



(a) single wall (b) wall-frame complex

Fig.3 Rebar Arrangement

Table.1 Material Property of Concrete

Item	XM,XR,YM	YR,XYM,XYR,PIT
Compressive Strength [MPa]	37.1	36.3
Young Modulus [MPa]	29400	26900
Tensile Strength [MPa]	3.36	3.04

widely used in Japan were listed in Table.2. Strictly speaking, the methods in Ref.[4] were not suitable for walls without side columns, however, it is still useful as a reference. From these values, the present specimens were recognized to be flexural failure type for out-of-plane loading (Y direction loading) and flexure-shear intermediate type for in-plane loading (X direction loading).

Loading pattern

The description of the test cases was tabulated in Table.3. Two test parameters, i.e., loading direction in the horizontal plane and the difference of monotonic or cyclic loading were both concerned with loading pattern. Six single wall cases were allocated to three kinds of loading direction which were composed of in-plane direction (X), out-of-plane direction (Y) and simultaneous bi-direction (XY). Displacement ratio of X:Y in bi-direction case was determined to be 1:5 so that intermediate failure mode between in-plane and out-of-plane will occur. Regarding cyclic loading case, a certain turning displacement was determined from the result of corresponding monotonic loading case as follows: The displacement where 90% of maximum load in XM case was attained in the hardening process for XR case, where 50% of maximum load was lost in the softening process for YR case, and where the sum of the vector of X direction load and Y direction load appeared maximum value in XYM case for XYR case. The same condition as XR case was planed to apply to other cases, however, the modification were introduced because no difference was found between XM and XR case. After cyclic load was given ten times at the basis of each turning displacement, specimen was pushed over until the supportability of vertical load was lost or any actuator reached its capacity.

Concerning wall-frame complex case, the specimen was subjected to cyclic load in X direction. The displacement where 20% of maximum load was lost in the softening process was adopted as the turning one.

The vertical load of 270kN and 460kN was given to single wall and wall-frame complex, respectively. These are both equivalent to 0.07 in the ratio of axial stress to concrete compressive strength.

Table.2 Expected Strength

Item	XM,XR,YM	YR,XYM,XYR,PIT
Compressive Strength [N/mm^2]	37.1	36.3
Young Modulus [N/mm^2]	29400	26900
Tensile Strength [N/mm^2]	3.36	3.04

Table.3 Test Cases

Specimen		Displacement direction X:Y	Laoding Pattern	Vertical Load [kN]
Single Wall	XM	1:0	Monotonic	270 (0.07)
	XR	1:0	Cyclic	270 (0.07)
	YM	0:1	Monotonic	270 (0.07)
	YR	0:1	Cyclic	270 (0.07)
	XYM	1:5	Monotonic	270 (0.07)
	XYR	1:5	Cyclic	270 (0.07)
Wall-Frame Complex	WF	1:0	Cyclic	460 (0.07)

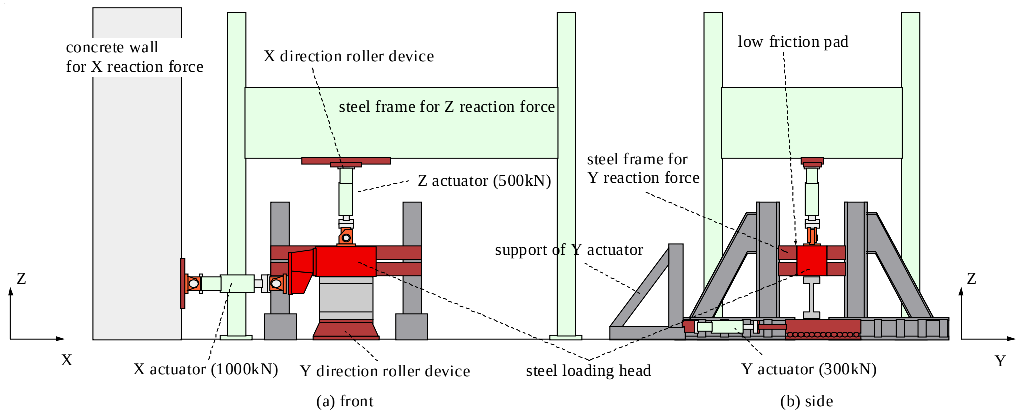


Fig.4 Loading Apparatus

Apparatus

Loading test apparatus is shown in Fig.4. L-shape steel loading head and 500kN actuator (Z actuator) were inserted above specimen. The upper edge of Z actuator was connected with a gate-style steel frame through an X direction roller device and the lower edge was connected with the loading head through a pin. In the side of specimen, 1,000kN actuator (X actuator) was connected with the above-mentioned L-shape loading head. Pins were added on both edges of X actuator. Y direction roller device was installed beneath specimen and 300kN actuator (Y actuator) was connected with that device. The reaction force against Y direction load was supported by triangular steel frames in the level of the loading head. Because low friction pads were attached on the contact surfaces, the loading head can move in X and Z directions. This apparatus enables to load in large displacement range without the axis rotation of actuators.

RESULTS

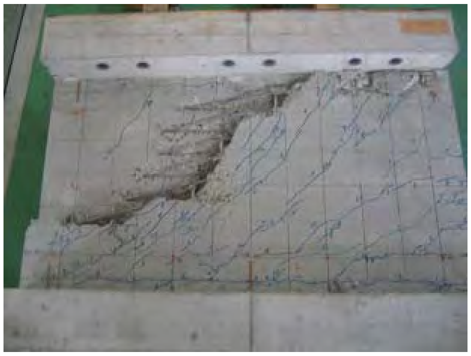
Main results on respective specimen are described in Table.4. The direction in which the actuator pushes specimen is defined to be positive. Crack patterns of XYM and WF case are illustrated in Fig.5. The relationships among horizontal displacement, vertical displacement and horizontal load are shown from Fig.6 to Fig.9. The detail failure process will be discussed later. Note that displacement values were corrected about move of devices after the tests so displacement ratio did not strictly satisfy X:Y=1:5 in Table.4.

Single wall under in-plane direction loading (XM and XR case)

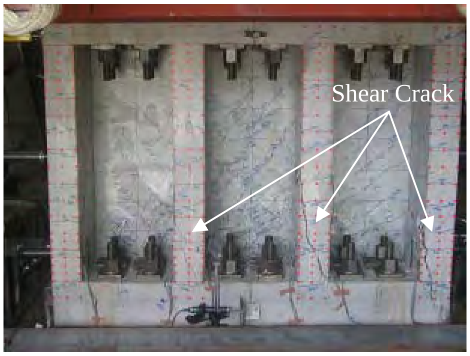
In XM case, inclined and flexural cracks were initiated at 200kN and 300kN, respectively. Maximum load was recorded under the displacement of 7.6mm (0.011 in deformation angle that can be obtained by the division of the relative displacement by the wall height) and then compressive yielding of vertical rebars and tensile yielding of horizontal ones were identified in the flexural compression zone. Concrete in that zone started to crush at the displacement of 13.4mm (0.019 in

Table.4 Test Results

Specimen		X Direction Maximum Load Point			Y Direction Maximum Load Point			Failure Mode
		Displacement [mm]	Deformation Angle	Load[kN]	Displacement [mm]	Deformation Angle	Load[kN]	
XM		7.58	0.011	493				Shear Compression Failure After Flexural Yielding
XR	+	10.05	0.014	466				Shear Compression Failure After Flexural Yielding
	-	-7.31	-0.010	-451				
YM					18.06	0.026	78.4	Flexural Failure by Rebar Breaking
YR	+				19.74	0.028	76.4	Flexural Failure by Rebar Breaking
	-				-22.18	-0.032	-72.6	
XYM		4.10	0.006	354	15.34	0.022	77.9	Out-of-plane Shear Failure
XYR	+	3.95	0.006	342	15.73	0.022	74.1	Out-of-plane Shear Failure
	-	-2.75	-0.004	-285	-14.38	-0.021	-71.4	
WF	+	9.90	0.014	722				Shear Compression Failure After Flexural Yielding (Wall Part) Shear Failure (Frame Part)
	-	-7.56	-0.011	-621				

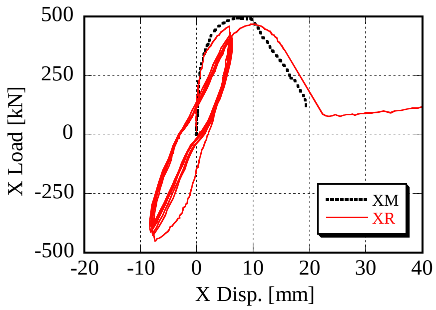


(a) XYM case

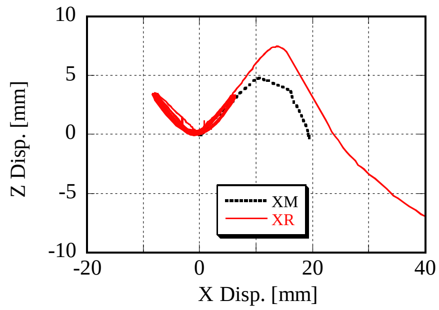


(b) WF case

Fig.5 Crack Pattern



(a) X displacement - X load



(b) X displacement - Z displacement

Fig.6 Test Results of XM and XR case

deformation angle). With displacement equal to 17.9mm (0.026 in deformation angle), remarkable falling of concrete spalls occurred and vertical displacement progressed downward drastically. In this final stage, the width of concrete crushing zone was reaching 2/3 of the wall width. XR case, which is cyclic case, presented almost the same failure mode and strength.

Single wall under out-of-plane direction loading (YM and YR case)

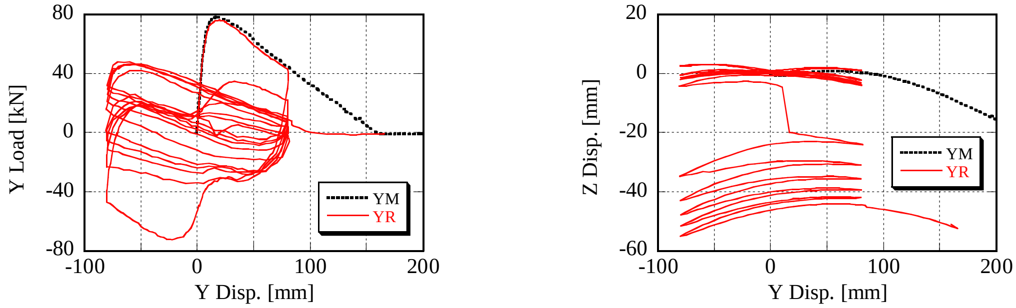
In YM case, tensile rebars yielded at the displacement of 7.3mm (0.010 in deformation angle) and concrete started to crush at 30.6mm (0.044 in deformation angle). Thereafter, the plastic hinges at both upper and lower edges rotated steadily without noticeable damage. The softening part in Fig.7(a) is solely owing to geometrical effect. In fact, the hardening trend was recognized when vertical index was converted to bending moment. Just before load reached zero, rebar breaking was sounded. The turning point for YR case was the state that the specimen had already suffered from concrete crushing and yielding of compressive rebars. Consequently, buckling of rebars at both upper and lower edges occurred and vertical displacement progressed downward in the cyclic loading process. Load reduced to zero in the earlier stage than YM case finally.

Single wall under simultaneous bi-direction loading (XYM and XYR case)

Both in-plane shear crack and out-of-plane flexural crack were observed in the initial stage. Vertical rebars started to yield from the corner in tension. At the moment when X displacement reached 4.7mm (0.007 in deformation angle), abrupt out-of-plane shear failure occurred in the compression zone against in-plane flexure. This is believed to arise from the concentration of shear force to the zone stiffened by increasing compression. The fatal out-of-plane shear crack spread all over the specimen soon and the lower edge of separated upper concrete block, which was barely tied by rebars bent out of shape, touched on the bottom stab of the specimen. XYR case traced almost the same failure process.

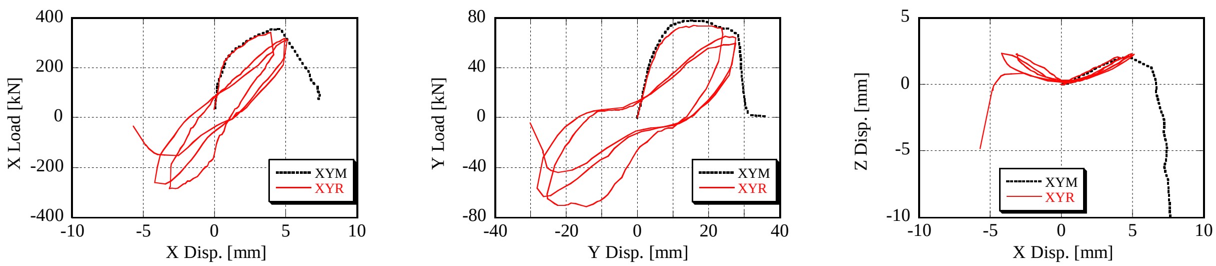
Wall-frame complex under in-plane direction loading

Before reaching the turning point, an inclined crack was first found on the wall surface in the center span. Horizontal tensile cracks appeared on the tensile side two frame members in the level from 400kN to 550kN. On the other hand, only one frame member closest to the compressive edge was intact. The compression zone of wall started to crush at 12.4mm (0.018 in deformation angle). After coming to first cyclic process, three frame members failed with inclined cracks at -7.6mm,



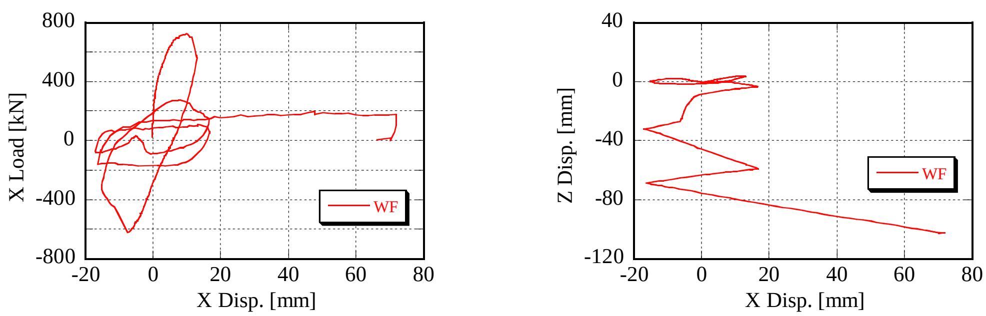
(a) Y displacement - Y load (b) Y displacement - Z displacement

Fig.7 Test Results of YM and YR case



(a) X displacement - X load (b) Y displacement - Y load (c) Y displacement - Z displacement

Fig.8 Test Results of XYM and XYR case



(a) X displacement - X load (b) X displacement - Z displacement

Fig.9 Test Results of WF case

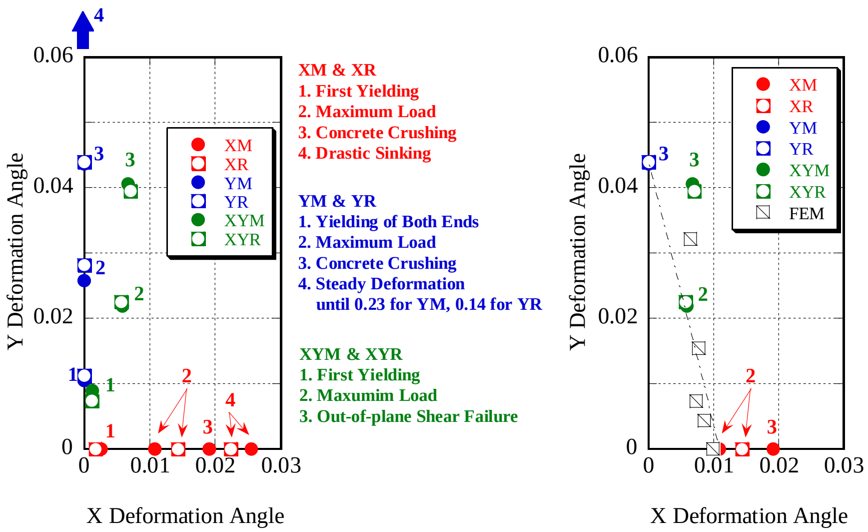
-11.4mm and -14.7mm (0.011, 0.016 and 0.021 in deformation angle), respectively. This continuous shear failure brought signicant reduction in structural strength. The damage continued to progress through first and second cycles. As vertical displacement advanced downward close to the capacity of Z actuator, the specimen was pushed over before ten cycles.

DISCUSSIONS

Limit deformation and Maximum Load in horizontal plane

Fig.10(a) shows the event points of all single wall cases in horizontal XY deformation plane. Sufficient ductility was displayed when horizontal load was given to exact out-of-plane direction, however, a little deviation brought brittleness. The fact that the most brittle mode was found in XYM case was should be noted in particular.

Numerical tests using nonlinear finite element method were conducted to examine in deep about loading conditions which were unrealized in the test. COM3[6][7] developed by Okamura and Maekawa was used for this examination. This program includes rigorous nonlinear constitutive laws about concrete and rebar, e.g. elasto-plastic and fracture model for non-cracked concrete, smeared crack concept for cracked concrete, tension softening model for concrete in the tensile zone, shear transfer model for aggregate interlock, average strain - average stress formulation for rebar and so on. Fig.11 shows the



(a) Test Results (b) Test and Analysis Results

Fig.10 Event Points in XY Deformation Plane

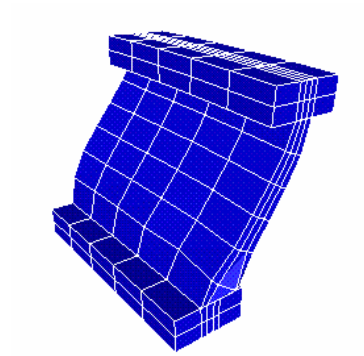


Fig.11 Analysis Model
(in Ultimate State)

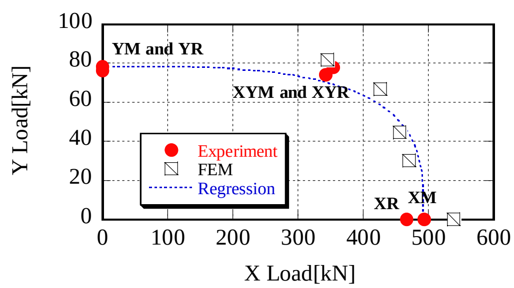


Fig.12 Maximum Load in XY plane

analysis model constructed based on second order solid elements. The ultimate state under the same loading condition as XYM case is illustrated in Fig.11 and failure similar to the test result was identified in the lower right part. Five patterns of loading direction between XM and XYM case were considered. The results of test and analysis were arranged together in Fig.10(b). The displacement where the maximum load appeared was taken among the analysis results and the plots from the test were focused on the events related to damage of concrete. The dashed line that links concrete crushing point about out-of-plane direction and maximum load point about in-plane direction forms a reliable limit.

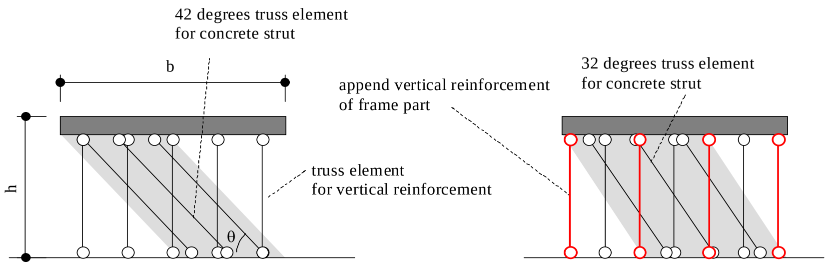
Fig.12 shows the maximum load in XY load plane with the analysis results. This figure indicates that maximum load about in-plane direction can also decrease due to the existence of out-of-plane component. Maximum load curve can be approximated by the family of ellipse as Eq.(1).

$$\left(\frac{V_x}{V_{x,max}}\right)^{\alpha} + \left(\frac{V_y}{V_{y,max}}\right)^{\alpha} = 1 \qquad (1)$$

where $V_{x,max}$, $V_{y,max}$ are strength in in-plane and out-of-plane direction. As for coefficient α, 3.31 was obtained by regression (blue broken line in Fig.12).

Effect of Combination of Wall and Frame

The maximum load of wall-frame complex was 229kN larger than that of XM case. The horizontal strength of frame part calculated on the base of the maximum load in YM case was 55kN. This difference is attributed to the combination effect of wall and frame. To discuss further simple truss models are developed as shown in Fig.13. One axial constitutive law of concrete and bi-linear curve are applied for strut and vertical truss, respectively. The angle of concrete strut θ is obtained



(a) Single Wall (b) Wall in Complex

Fig.13 Simple Truss Model to Interpret Strength Increase in WF case

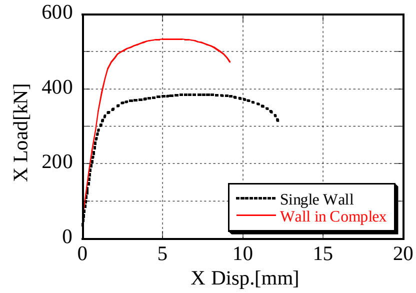


Fig.14 Result of Truss Analysis

from the condition to maximize shear force V in Eq.(2) as long as vertical component of compression force acting to strut was maintained according to Ineq. (3).

$$V = \nu f_c \left(b - h\tan\theta\right)\cos\theta \cdot d\sin\theta \tag{2}$$

$$\nu f_c \left(b - h\tan\theta\right)\cos\theta \cdot d\cos\theta \le f_y pbd + N \tag{3}$$

where ν is concrete compressive strength reduction factor (0.6 close to the minimum value in general use was assumed here), f_c is concrete compressive strength, b, d and h are width, thickness and height of wall, respectively, f_y is yield strength of rebar, p is effective reinforcement ratio, and N is vertical load. As a result, the difference of two models was 149kN as shown in Fig.14 and the increase of strength can be explained. Although the contribution of horizontal rebars was neglected for simplicity, the half of their full strength seemed to be displayed in the experiment when estimating from the difference between actual XM case and the truss model for single wall.

On the other hand, the rather negative effect in which frame members failed by shear was identified in terms of deformation performance. Shear failure of them can not be caused if wall and frame is separated as understood from Table.2 and the actual test results of YM and YR case. Considerable causes are the following two items both accompanied by crushing of concrete in the lower part of wall. First, shift of the area supporting vertical load from wall to frame raised the flexural strength of frame members. Second, the lower part of frame members formed short columns because the wall and frame were kept bundled in the upper part.

Effect of Cyclic Loading

Three failure modes were observed approximately in the present test as shown in Table.4. Single walls of XM and XR case and wall part of WF case showed shear compression mode. In XR case, in which cyclic loading was given prior to maximum load point, cyclic loading hardly contributed to the following behavior in spite that rebars had already yielded partially when it started. Indeed, the load reduction at the turning point converged into the range from 0.85 to 0.9 as shown in Fig.15 and load was restored in the stage after cyclic loading. On the contrary, the strength degraded drastically through a few cycles in WF case which had the turning point in the post-peak region. YM and YR specimens showed flexure mode, which was not sensitive to the property of concrete. The plots for YR in Fig.15 are based on bending moment to remove the geometrical effect. Although damage was accumulated in the cyclic loading stage of YR case, the trend to converge is still identified. XYM and XYR specimens showed shear tension mode. In these cases the arrival at maximum load point and drastic load reduction were the simultaneous events as concrete subjected to one axial tension.

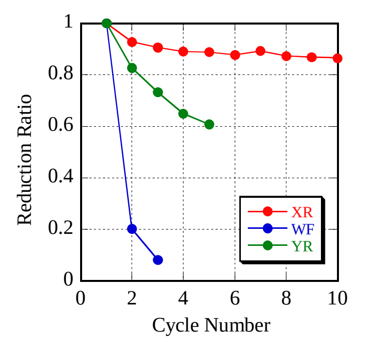


Fig.15 Relationship between Cycle Number and Load reduction ratio

The point through all cases is summarized as follows. The effect of cyclic loading is insignificant about any direction until the damage of the concrete contributing to resistance mechanism appears even if rebars are yielding. However, after the concrete starts to be damaged, cyclic loading progresses damage accumulation remarkably except for the case of exact out-of-plane direction.

CONCLUSIONS

Horizontal bi-direction loading test for six single walls and in-plane direction loading for a complex of wall and three-span frame were conducted to investigate the mechanical property of reinforced concrete walls used as a member of box culvert in three dimensions. The followings were obtained from the test results:

1. In horizontal XY deformation plane the line that links concrete crushing point about out-of-plane direction and maximum load point about in-plane direction formed a reliable limit to save single walls from failure.
2. In horizontal XY load plane maximum load curve was approximated by the family of ellipse.
3. Wall-frame complex displayed the increase of strength by their combination, but on the other hand, the negative aspect that shear failure occurred in frame members was identified.
4. The effect of cyclic loading was insignificant about any direction until the damage of the concrete contributing to resistance mechanism appeared even if rebars were yielding.

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