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EXPERIMENTAL STUDY ON P-DELTA EFFECT IN RC HIGH RISE BUILDING

M. A. A. Mollick [1]

ABSTRACT : There are a very few experimental studies on the P-Delta effect. This paper reports the *P-Delta* effect through the test on three one-fourth scale reinforced concrete frame structure models which represent the lower part of high rise building subject to seismic force. The test results within the scope of this study revealed that the *P-Delta* effect should be included in the analysis for the design of a high rise building if the story drift exceed 1/85 rad. during an expected earthquake excitation in seismic region. The test results also revealed that a rigorous analysis should be carried out rather than to use the conventional equations for the prediction of member strength whenever such a high rise building is to be designed.

KEY WORDS : High rise building, exterior column, seismic force, story drift, *P-Delta* effect.

INTRODUCTION

Whenever a high rise building is shaken by the earthquake excitation, the exterior columns are subjected not only to the lateral force but also to the fluctuating axial force both in compression and tension. Naturally the lowest part of the exterior columns are most severely subjected to the highest intensity of axial force. The combine effect of story drift in the lateral direction due to the lateral force and the axial force causes the well known *P-Delta* effect. The *P-Delta* effect becomes more severer with higher story drift. As shown in Fig. 1, the total effects on the exterior columns are due to the combination of lateral force and the *P-Delta* effect.

Analytical studies on the *P-Delta* effect are reported by MacGregor and Hage (1977), and Gaiotti and Smith (1989). But there are a very few experimental studies on the *P-Delta* effect, one of them reported by Ford, Chang and Breen (1981), which was a study on single story frame. Experimental studies on multistory reinforced concrete frames were documented by Shimazu and Mollick (1991), and Mollick and Shimazu (1990) from the viewpoint of the long-term axial force level and the stability problem of continuous columns. Since in these two studies, experimental measurement of the vertical load carrying capacities of columns were made by applying monotonous increment of axial load, their data may be a supportive materials for the study on the *P-Delta* effect.

1 Technical Research Institute, Yokohama, 224 Japan

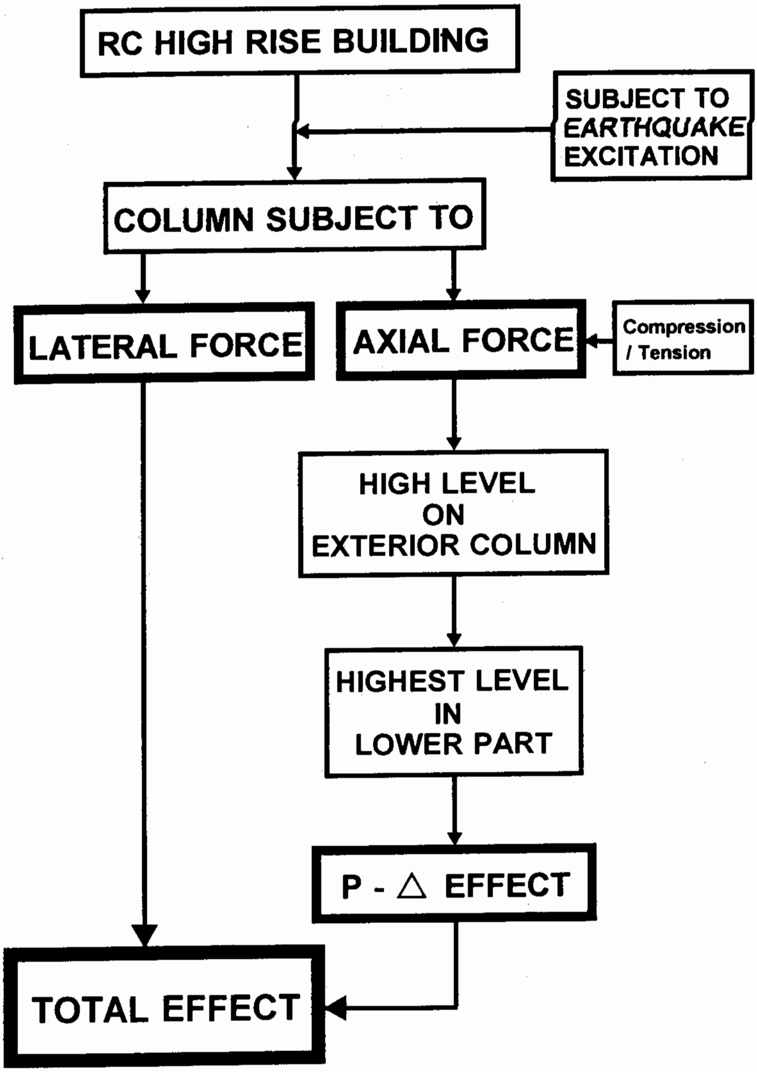

Fig 1. P-Delta Effect Leads to Total Effect

An experimental study on six reinforced concrete test structure frames were conducted in the early years of 1990s at the Technical Research Institute of Fujita Corporation, Japan by a group of researchers including the author, to know the response behavior of the frames under high intensity seismic loading. The study had been reported by Teraoka et. al. (1993) addressing the overall response behavior of all the six test structures, which included a little study on the *P-Delta* effect.

This paper has been written with the aim of highlighting only the *P-Delta* phenomena by using three of the six test structures. The selected three test structures represent the typical ones, which are sufficient to address the response on the *P-Delta* effect within the scope of this study.

MODELING OF TEST STRUCTURES

Figure 2 shows the aforementioned axial force on exterior and interior columns of a 30-story building in a distributed format along the

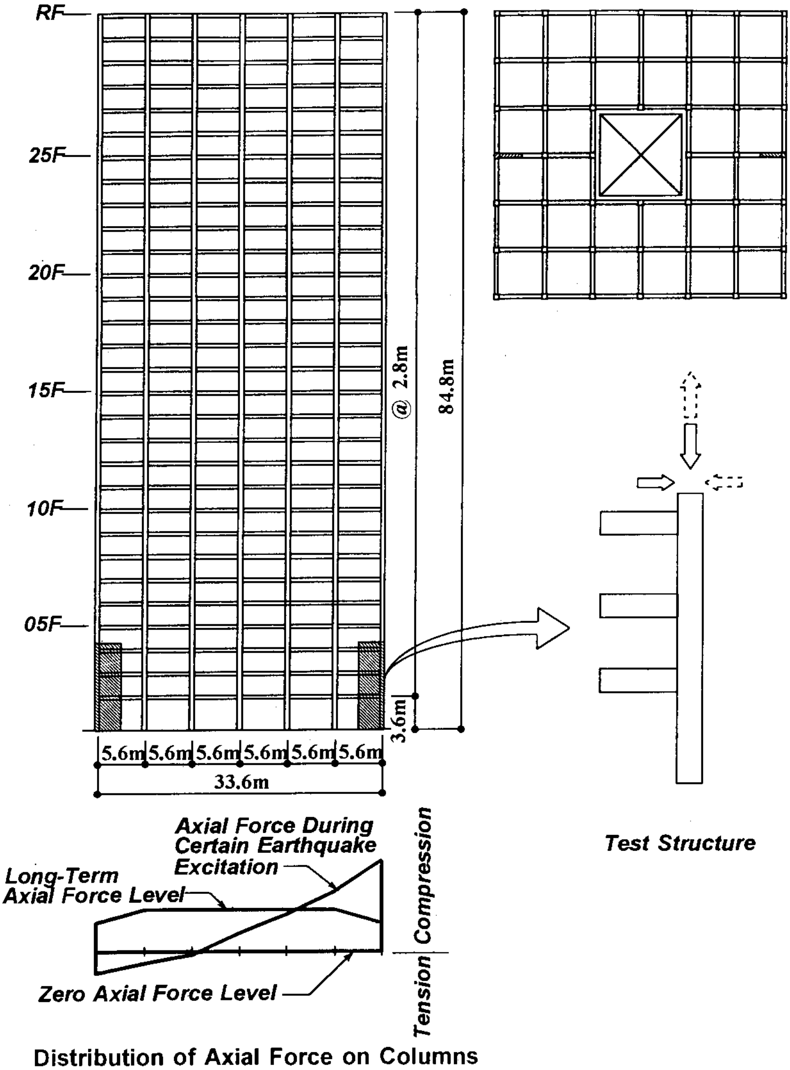

Fig 2. Modeling of Test Structures from a High Rise Building

lateral projection of the building. One of the curves show the axial force during certain earthquake excitation. Practically, this curve fluctuates at every instant until the end of excitation. Since the exterior columns are subjected to most severe condition, the lower part subassemblage of the exterior column with three half-span beams shown by the shaded area has been modeled as the test structures scaling down to one-fourth of their actual size.

When the shaking take place from left to right direction, the right side exterior column is subjected to compression while the left one to tension, and vise versa. Therefore, the exterior columns are subjected to both in compression and tension force during the shaking in alternative sequence. The distribution of bending moment under the compression and tension force take the form as shown in Fig. 3. As shown in this

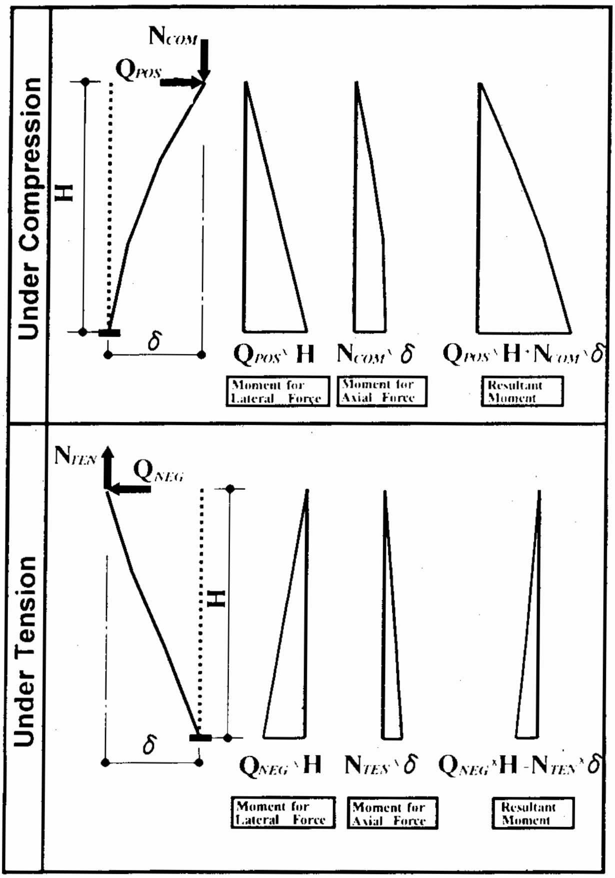

Fig 3. Bending Moment Distributions of an Exterior Column Subject

figure, the column is subjected to higher bending moment under compression than under tension, because the *P-Delta* effect is being added to the lateral effect under compression but deducted under tension.

The test structures were prepared for the application of repeated reversal lateral load on frame with variable intensity of axial force on the column. The combination of the two loads represent the seismic type loading. It is understandable that if a multispan frame with actual number of stories could be modeled for the test, more reliable test results could be expected.

TEST STRUCTURES

The selected three test structures are labeled by EF-1, EF-2 and EF-5. The cross sectional properties and overall geometry of columns and beams are shown in Fig. 4. Two 10 mm and two 13 mm deformed main bars at the top and bottom, and 5 mm plain stirrups at 60 mm on center were used in the three beams. Four 13 mm and twelve 10 mm deformed main bars and 5 mm plain hoops at 55 mm on center were used in the column. As shown in the Fig. 4, the main bars of the beams were anchored inside the beam-column joints as L-shaped form supported by eight additional anchorage bars in the case of EF-1 and EF-5 and as U-shaped form in the case of EF-2.

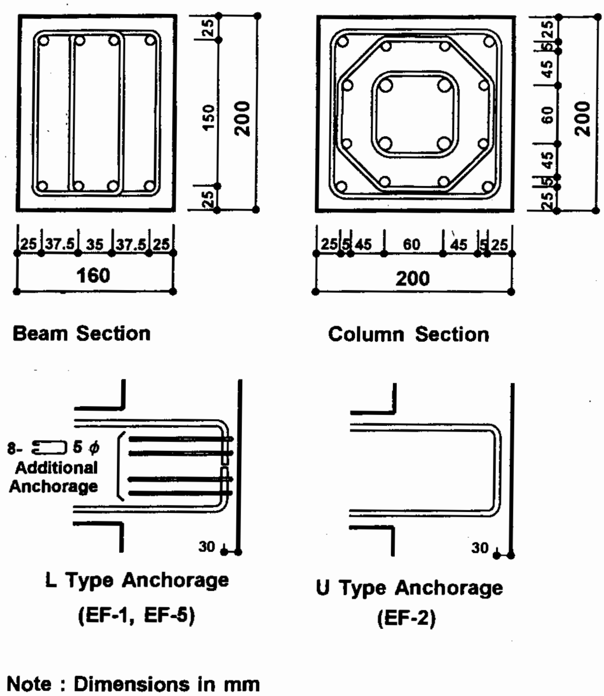

Fig 4. Cross Section Properties of Beam, Column and Joint (Adapted from Teaoka et al. , 1993)

The yield strengths and elastic modulus of 13,10 and 5 mm bars were 480 and 205000 MPa, 340 and 185000 MPa, and 290 and 205000 MPa respectively. The compressive strength and elastic modulus of concrete used for the construction of the test structures were 45 and 31500 MPa.

A total number of 195 strain gages were attached at the strategic locations of the main bars, stirrups and hoops to measure their response behavior, most of the data are not available in this paper.

TEST PROCEDURE

The test structure with loading system and other principal instrumentation are shown in Fig. 5. Three 195 kN load cells were installed in between the inter-stories at the end of three beams to measure the reactions. A combination of a 1175kN loading jacks and a 490 kN load cell was set at both left and right side of the stub in the horizontal direction for the application of lateral load on the test structure frame. Another combination of a 1175 kN loading jack and a 980 kN loading cell was set at the top of the test structure in the vertical direction for the application of compression/tension axial load on column. Lateral load applied by the left and right side jacks are to be addressed as positive and negative lateral load respectively. Compression and tension axial load applied by the vertical loading system are to be addressed as positive and negative axial load respectively. A total number of 59 displacement transducers (DT) were installed at the strategic locations of the test structure to measure the displacement and deformation responses, but most of them are not shown in the figure.

At the very beginning of loading, compression axial load equivalent to the gravity load of $+0.15f'_cbh$ (270 kN) was applied on column. Then positive lateral load on frame and compression axial load on column were gradually increased in simultaneous operation. The former was controlled by the displacement reading (δ_T) at the mid level of the 4th floor and the latter was controlled by following a relation of $N = 15Q_{OT} + 28$. In the first cycle, the lateral load was applied up to the story drift of $+2.5 \times 10^{-3}$ rad. (story drift $R_T = \delta_T / H$. Then the lateral and axial loads were gradually released to zero observing the reading of horizontal and vertical load cells. At this stage of zero load, negative and tension axial load on column were simultaneously increased, provided that the tension axial load was controlled by following a relation of $N = 25Q_{OT} + 28$. The lateral load was applied up to -2.5×10^{-3} rad. of story drift. Then the lateral and axial loads were released to zero as mentioned before. At this stage, one complete cycle of loading with story drift of $\pm 2.5 \times 10^{-3}$ rad. was carried out. Following this procedure, three cycles of ± 2.5, ± 5.0, ± 10.0, ± 20.0 ($\times 10^{-3}$) rad., two cycles of $\pm 30.0 \times 10^{-3}$ rad., and one cycle of $\pm 50.0 \times 10^{-3}$ rad. means a total number of fifteen cycles of loading were applied on a test structure frame. The limitation of the maximum compression and tension axial load applied on the column were $+0.50f'_cbh$ (900 kN) to $-0.12f'_cbh$ (215 kN) for EF-1 and EF-2, and $+0.39f'_cbh$ (700 kN) to $-0.03\ f'_cbh$ (50 kN) for EF-5.

The lateral load applied by the horizontal jacks at the left and right sides are denoted by P. The horizontal component of the load N' is denoted by Q_N. Then the resultant lateral load on the frames are obtained as $+Q_{OT}$ and $-Q_{OT}$ by using the geometrical linearity as shown in the Fig.5.

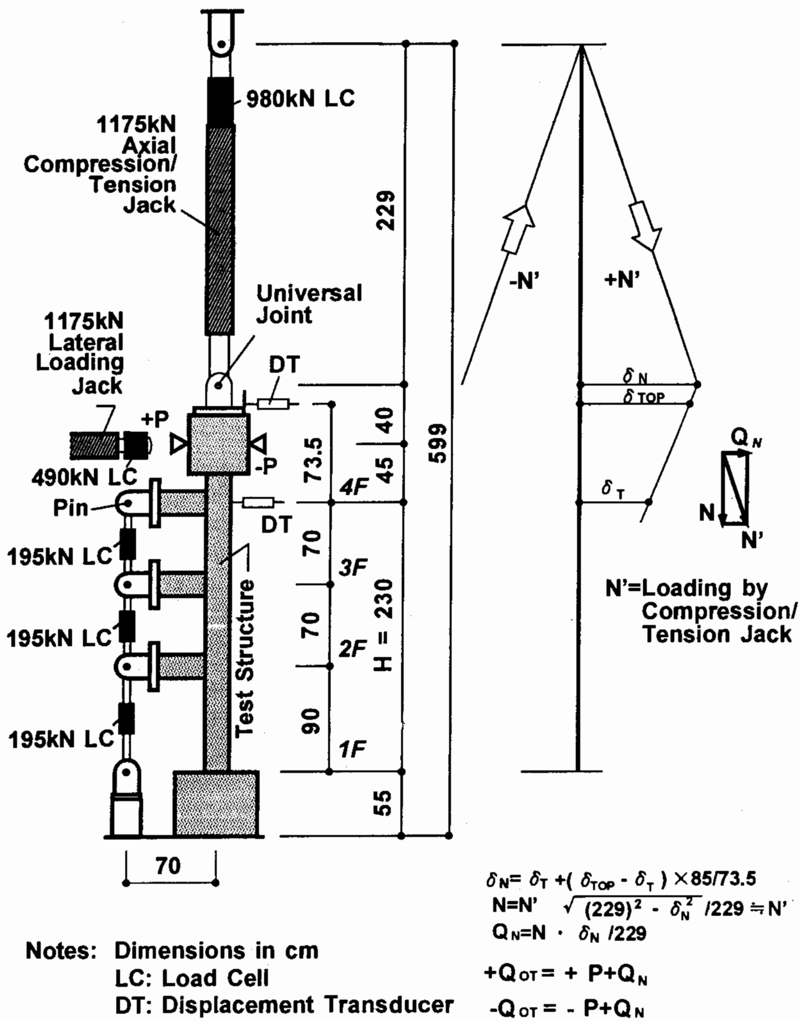

Fig 5. Test Structure Geometry and Loading System (Adapted from Teaoka et al., 1993)

The test was conducted by adopting static loading system mainly because of the application of high intensity axial load on column of such a subassemblage frame. Such high intensity axial load could not be applied on the column if the test was conducted by adopting dynamic loading system. Although the static loading test gives a little lower value of lateral strength, may be around 10%, but important data during the loading operation could be recorded especially on the gradual appearance of creaks at different locations, which is very important for a subassemblage test structure.

TEST RESULT INTERPRETATION ON *P-DELTA* EFFECT

(a) Lateral Strength-Story Drift

Figure 6 shows the hysteretic relationship between Q_{OT} and total story drift R_T. All the test structures show a common trend that during positive loading, declination of strength appeared after the attainment of maximum lateral strength but during negative loading no declination of

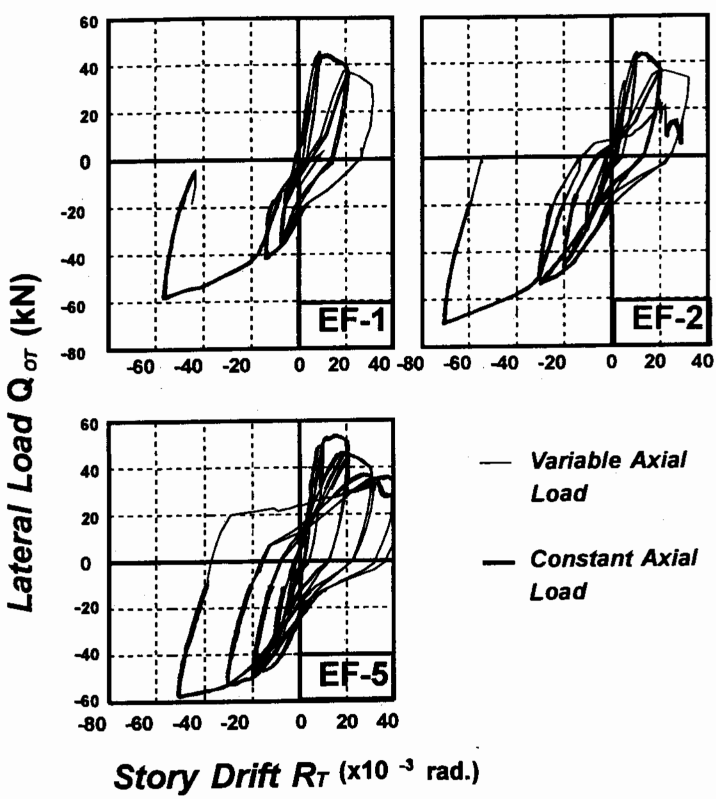

Fig 6. Lateral Load versus Story Drift (Adapted from Teraoka et al. ,1993)

strength appeared until the end of test. This trend clearly show that during positive loading the *P-Delta* effect worked on the test structures. EF-1 and EF-2, which were subjected to higher intensity of axial load than EF-5, showed more unstable response during positive loading, which indicate that the more axial force acted upon the column over the height of a frame, the more instability due to the *P-Delta* effect is likely to occur.

Table 1 show s the numerical values of maximum strengths and their corresponding story drifts under both the positive and negative loading. This table also includes the calculated values of maximum strengths. The calculated values were obtained by a simple equilibrium equation as follows :

$$Q_{cal} = (\Sigma M_{by} + M_{cy} \pm N \cdot \delta_T)/H$$

where, Q_{cal} : calculated maximum lateral strength of the frame, M_{by} : yield strength of beams in the frame, M_{cy} : ultimate strength of column. The M_{by} an M_{cy} are calculated by following the Reinforced Concrete Code of the Architectural Institute of Japan (1982). Under positive loading, the measured values are lower than the calculated values, especially this lower trend of EF-1 and EF-2, which were subject to higher intensity of axial load, is higher than EF-5 which was subjected to comparatively lower intensity of axial load. But under negative loading, the trend under positive loading is approximately reversed. This phenomena has revealed that since due to the higher intensity of axial force the exterior columns are subjected to the *P-Delta* effect, rather a rigorous analytical procedure should be followed in the calculation of the response behavior of the frame in a high rise building, not by using the conventional equations.

Table 1. Maximum Lateral Strength and Corresponding Story Drift

Test Structures	Measured				Calculated			
	$+Q_{OT}$ (kN)	$+R_T$ (10^{-3} rad)	$-Q_{OT}$ (KN)	$-R_T$ (10^{-3} rad)	$+Q_{cal}$ (kN)	$-Q_{cal}$ (kN)	$\frac{+Q_{OT}}{+Q_{cal}}$	$\frac{-Q_{OT}}{-Q_{cal}}$
EF-1	43.6	7.1	55.7	56.7	55.4	56.5	0.79	0.99
EF-2	44.3	13.6	68.7	45.9	49.5	54.1	0.89	1.26
EF-5	52.6	14.6	55.7.6	50.7	52.8	51.3	0.99	1.08

Notes : R_T = total story drift = δ_T/H
Q_{OT} = measured lateral load on frame
Q_{cal} = calculated lateral strength of frame

During positive loading, the maximum strength attained by EF-1, EF-2 and EF-5 at the story drift of 7.06, 13.60 and 14.60x 10^{-3} rad. respectively (Table 1). Since the three test structures differ by two different parameters which follow their response behavior, so if an average value of story drift for the three test structures is estimated, it becomes 11.6 x 10^{-3} or 1/85 rad. Therefore,in the analysis for the design of a high rise building whose exterior columns are subjected to the intensity of axial force in the range mentioned in the section of 'test procedure', the *P-Delta* effect should be included if the story drift exceed 1/85 rad. This result very closely agree to the value of 1.80 rad. recommended by Otani et al. (1994).

(b) Bending Moment and Shear Force

Figure 7 show the bending moment and shear force at the first floor of the test structures EF-2 and EF-5 when they attained story drift of 10

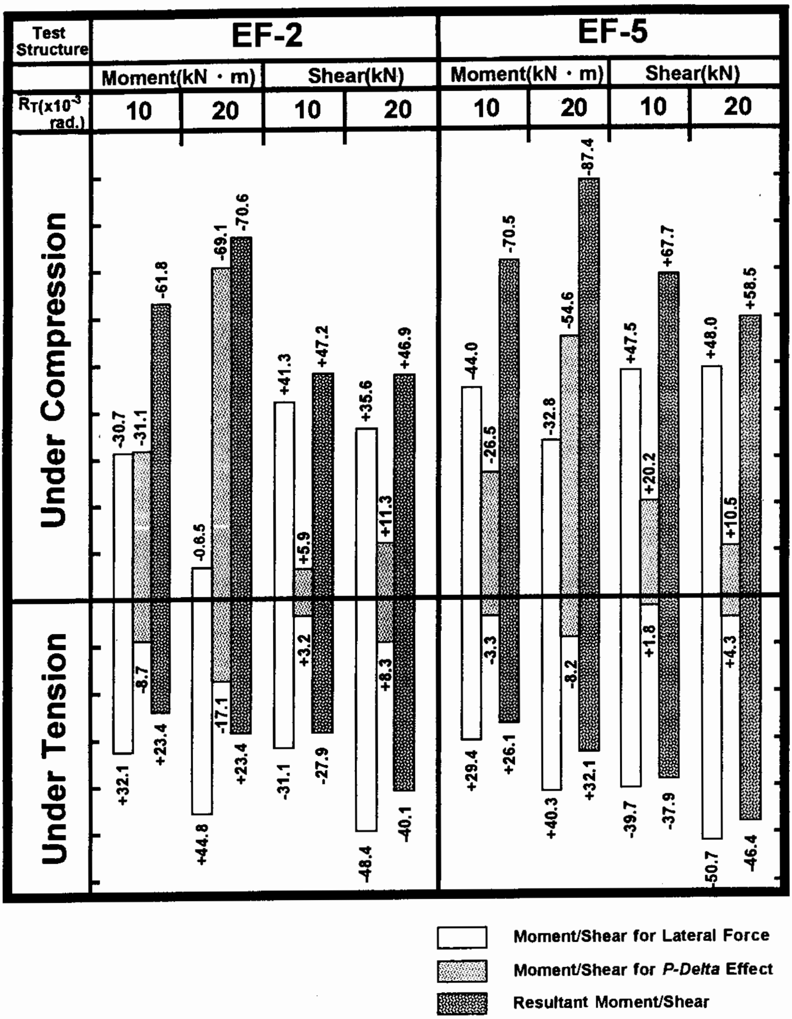

Fig 7. Bending Moment and Shear Force at Lower End of 1st Floor

and 20 x 10^{-3} rad. The moment and shear due to lateral and axial loads, and their resultants are plotted separately. As can be seen from the figure, due to the effect of the *P-Delta* under compression, the resultant moment changes dramatically (for reference see Fig. 3). And this tendency is more severer at the higher story drift of 20 than 10 x 10^{-3} rad. This figure reveals more clearly that it is most essential to include the *P-Delta* effect during the design of a high rise building subject to seismic force.

The shear force due to the *P-Delta* effect is not considerably increased under compression. But the effect is to be taken into account when analysis in the design of a high rise building is being carried out.

(c) Effect on Anchorage Method

The test structures EF-1 and EF-2 were different in their anchorage method (see Fig. 4) but subjected to the same axial load. They show almost the same maximum lateral strength at different story drifts during positive loading (see Table1). Although the test structures EF-2 showed a little better ductility than EF-1 but its U anchorage exhibited slippage from bent portion towards tail as examined after the test. Therefore, it could not be made clear which method of anchorage had better performance on the *P-Delta* effect but the L type anchorage with additional bars showed favorable response.

CONCLUSIONS

Three test structures representing the lower part of a high rise reinforced concrete building and composed of exterior column and three half span beams subjected to seismic loading, were studied to know the response behavior especially in respect to the well known *P-Delta* effect.

The test result revealed that it is most essential to include the *P-Delta* effect in the analysis for the design of a high rise building subject to seismic force. Especially the *P-Delta* effect becomes more important to take into account if the story drift of a high rise building exceed 1/85 rad. during an expected earthquake excitation in seismic region as found within the scope of this study.

The test results also revealed that a rigorous analysis should be carried out whenever such a high rise building is to be designed rather than to use the conventional equations for the prediction of member strength.

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CONVERSION FACTORS FROM SI TO INCH-POUND

1 cm = 0.3937 inch

1 kN = 0.2248 kip

1 MPa = 0.1450 kip per sq-inch

1 kN-m = 8.8495 kip-inch

NOTATIONS

b = breadth of column section

f'c = compressive strength of concrete

h = height of column section

H = height of frame up to mid level of 4th floor beam (230 cm)

M_{by} = yield strength of beam

M_{cy} = ultimate strength of column

N = vertical component of N' act as axial load on column (Fig.5)

N' = load applied by 1175 kN compression/tension jack (Fig.5)

N_{COM} = compression load on column

N_{TEN} = tension load on column

P = lateral load applied on frame at the center level of stub

Q_{cal} = calculated lateral strength of frame

Q_N= horizontal component of the load N' (Fig. 5)

Q_{OT} = measured lateral load on frame

Q_{pos} = horizontal load in positive direction

Q_{NEG} = horizontal load in negative direction

R_T = total story drift

δ= horizontal displacement of frame at top level (Fig. 3)

δ_N = displacement of frame at the level of universal joint (Fig. 5)

δ_T = displacement at the mid level of 4th floor beam

δ_{TOP} = displacement at the top of frame (Fig. 5)