- Technical Paper -

RESPONSE PREDICTION AND EXPERIMENTAL RESULTS OF A ONE-BAY REINFORCED CONCRETE FRAME

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ABSTRACT

A one-bay reinforced concrete frame was tested under varying axial load and cyclic lateral loads. Prediction of the test results was implemented prior to the test. A flexure response was predicted applying Axial-Shear-Flexure Interaction (ASFI) method. Based on ACI and AIJ equations, a shear failure was estimated for the frame response. However, experimental results verified estimated performance by ASFI method. Considering an effective length for the columns, due to movement of the inflection points, a satisfactory correlation was obtained for both analytical and test data.

Keywords: Axial-shear-flexure interaction, displacement-based analysis, shear and flexure failures, experimental study, frame structure, axial deformation, ultimate drift ratio.

1. INTRODUCTION

A reinforced concrete frame with two columns, named RCF, is tested under constant average axial load and cyclic lateral loads, in order to verify a new analytical model, entitled ASFI method [1]. Axial-shear-flexure interaction method is based on coupling shear and flexure models considering axial deformations interaction, satisfying compatibility and equilibrium conditions. The specimen is designed considering a mid-frame at the first story of a 6-story building based on the old design code of Japan, as shown in Fig.1. A nonlinear displacement analysis was implemented for the frame prior to the test by applying axial-shear-flexure interaction (ASFI) method [1]. Based on equations in ACI and AIJ for shear capacity of reinforced concrete columns, a shear failure was expected to dominate the behavior of the frame. However, prediction by ASFI method indicated a flexure behavior for the specimen. The test was carried out for the reinforced concrete frame subjected to the designated loads and as the results, a flexure performance was observed, as it was predicted by ASFI method. Details of the experimental study and analytical outcomes are presented in the following sections.

2. TEST PROGRAMS

2.1 Specimen Details

Prior to this experimental study, a reinforced concrete shear wall, including two boundary columns, was designed and tested, representing a 1/3-scale-mid-frame wall of a 6-story building based on old Japanese code regulations [2]. For analogy, the same scale of the frame is constructed for this experimental study, however, without shear wall. Overall configuration of the specimen RCF is depicted in Fig. 2. The two columns of the frame specimen have cross-section of 250mm×250mm and height of 1400mm. Table 1 gives details of the main bars and transverse reinforcement properties of the two columns. Top and bottom stubs have section of 500mm×400mm with 8-D19 as main bars and 4D10@100 as hoops.

Table 1 Reinforcements of Columns

Type	Yielding strength (MPa)	Reinforcement ratio %	Bars
Main Bars	385	1.82	16-D10
Hoops	330	0.10	D4@100

Three cylinder compression tests were implemented for concrete at age of 90 days, one week before the test. An average of 20 MPa peak

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compression stress was obtained for the concrete samples. Furthermore, an average strain of 0.0018 at peak compression stress was derived from the test data for the concrete.

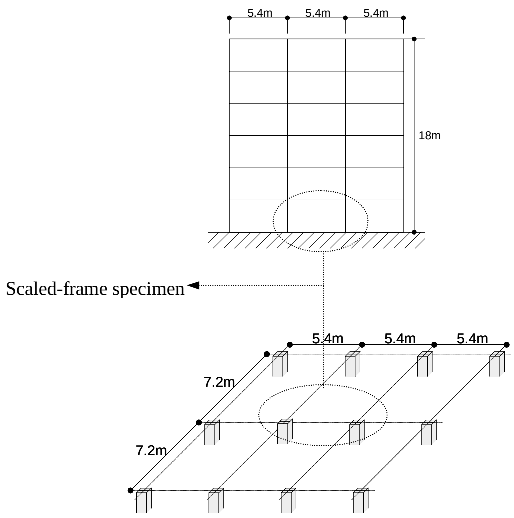

Fig.1 Location of scaled-frame specimen RCF in the full scale 6-story building

Fig. 2 also illustrates details and locations of transducers installed on both side of the columns to measure deformations related to curvatures along the columns. Distances between centroid of the columns to the axis of the transducers, depicted in the figure, are measured as built before starting the test.

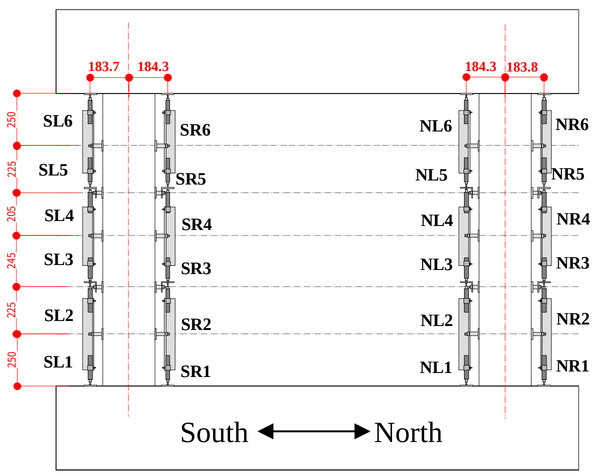

Fig.2 RC frame specimen and transducers for measuring flexural deformations

Locations of the curvature transducers are restricted by the location of reinforcements in the columns. Therefore transducers have different distances from each other along the height of the columns. Basically, top and bottom transducers are placed in the D distance, depth of the section. Others are placed in the closest possible position to the center, considering the location of steel bars.

Fig. 3 shows transducers installed for measuring drift, diagonal deformations and axial deformations.

2.2 Experimental Setup and Loading

For a reinforced concrete frame subjected to a lateral load such as earthquake or wind, axial loads in columns are varying related to the lateral load, considering lateral load distribution along the height of the building.

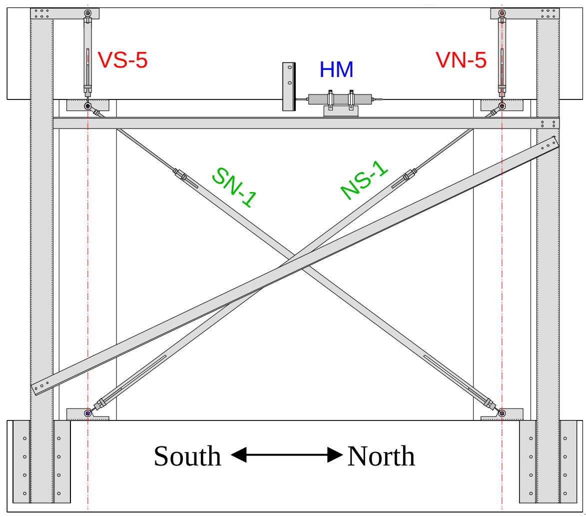

Fig.3 Transducers for axial deformation and drifts as well as diagonal deformations

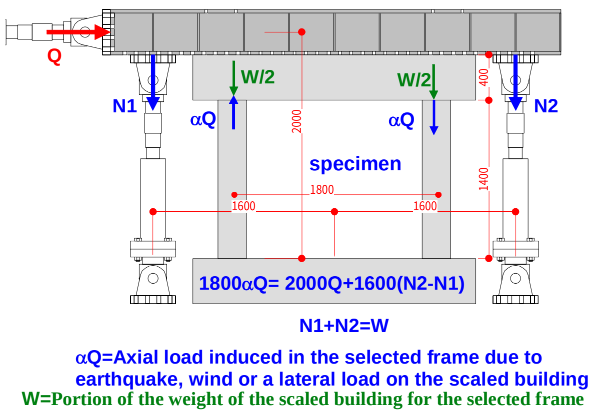

Fig.4 Loading Setup for Specimen RCF

The selected specimen is a mid-frame; therefore considering a frame system in the entire building, variation of axial loads in the columns is lower than those of the boundary columns. Assuming coefficient α as the ratio of the designed height of the applied lateral load on the specimen to the span of the frame, variation of axial load for each column is considered as αQ. Axial load due to the portion of the scaled-building weight, w, on the selected frame, should be added to the varying axial loads due to lateral load. Fig. 4 shows details of the above-explained axial loads computation. In this experimental study, the portion of building-weight applied on both columns of the specimen frame is determined as w=600kN. Coefficient α is assumed equal to 1.0 for this experimental study. Axial load is computed and applied simultaneously as lateral load is applied to the specimen. For the test, lateral load was controlled based on displacement. Drift ratios at peaks in two lateral loading directions were ±1/400, ±1/300, ±1/200, ±1/150, ±1/100, ±1/75, and +1/58 (columns failed at this drift ratio).

3. ANALYTICAL ESTIMATION

3.1 Axial-Shear-Flexure Interaction Approach

The new simple analytical approach [1], developed based on axial-shear-flexure interaction, ASFI method, is applied in this study in order to estimate displacement-based response of the specimen. An axial-shear model and an axial-flexure model are coupled and formed the ASFI element. Fig. 5 illustrates the two models of axial-shear and axial-flexure and their axial interaction by means of springs in series. The same constitutive laws and material properties are applied for the two models. Fig. 6 shows ASFI method, simplified for a reinforced concrete column, including equilibrium and compatibility conditions.

Total axial deformations considered in ASFI method are axial strains developed by, axial, shear, flexure and pullout mechanisms. Total drift ratio is a combination of shear, flexure and pullout deformations as shown in Fig. 7. Applying the simplified ASFI method for columns, displacement-based response was estimated for the specimen RCF prior to the test. The results are presented in the next section.

3.2 Response Estimation Prior to the Test

Prior to the test, shear and flexure capacity of the reinforced concrete frame was predicted based on ACI and AIJ equations. According to the computation results, a shear failure was predicted for the specimen. Later, lateral load-drift ratio response of the RC frame was estimated by ASFI method [1], [2]. However, the results of ASFI analysis indicated a flexural response. Fig. 8 illustrates all the results predicted by AIJ, ACI and ASFI approach. Two analyses were carried out with different expected concrete and steel bars strengths (10% different) and also different tensile constitutive laws, applicable in ASFI method.

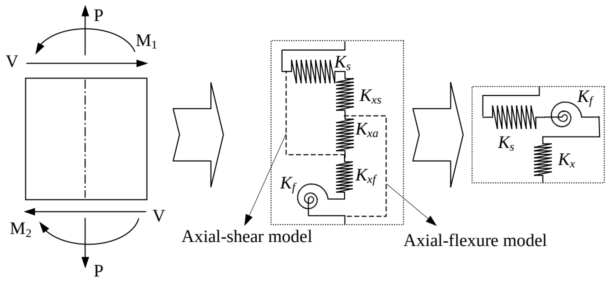

Fig.5 Springs Model of ASFI method

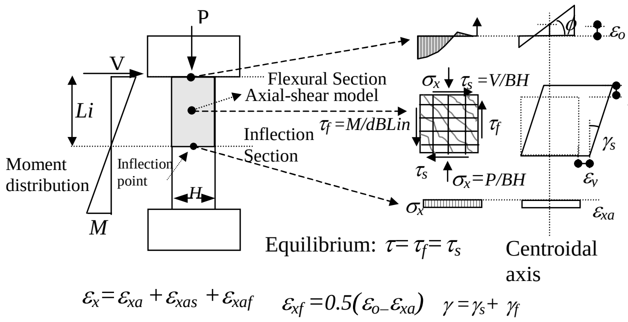

Fig.6 Axial-shear-flexure interactions in ASFI method

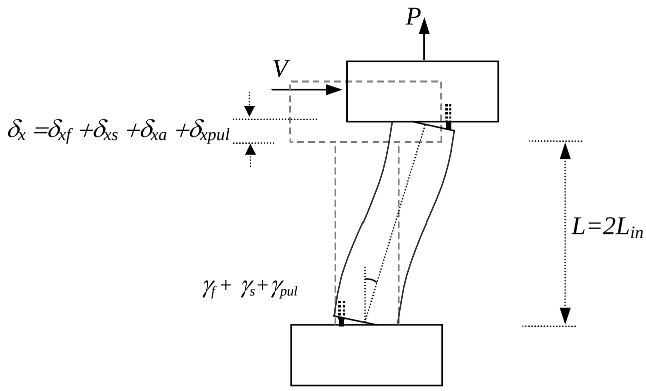

Fig.7 Axial and shear deformations of a column considered by ASFI method

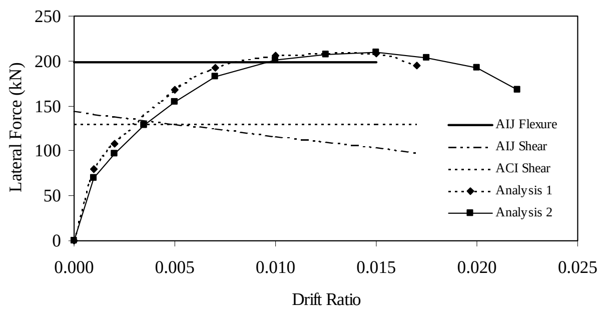

Fig.8 Results estimated by AIJ, ACI and ASFI methods prior to the test

It is important to mention that in all the computations for the above analyses the height of 1400mm is considered for the column with inflection point at the middle height of the columns. Fig. 9 shows specimen RCF before the test and the estimated results attached on the top of the frame.

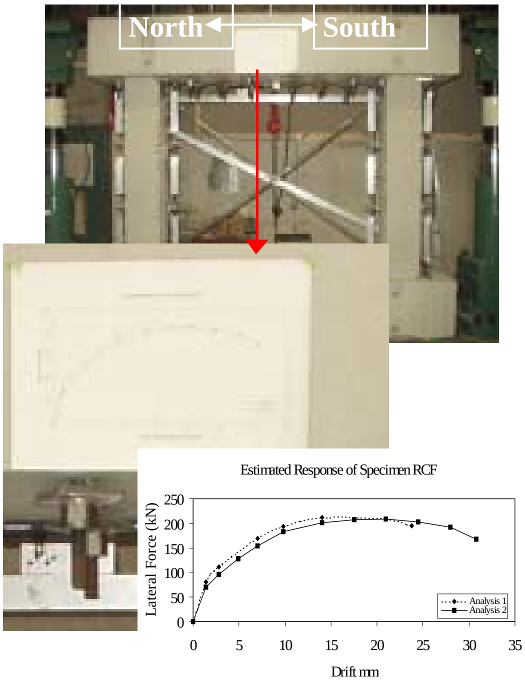

Fig.9 Specimen RCF before the test with the estimated analysis attached on the top stub

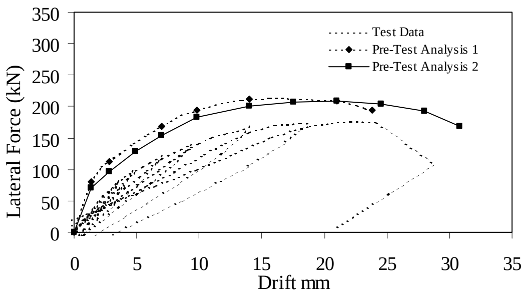

Fig.10 Comparison of the pre-test analytical results and test data

4. TEST AND ANALYTICAL RESULTS

Based on the test results, maximum lateral load capacity of the frame was about 185kN in the negative direction and a maximum of 175kN in positive direction of loading. Which shows about 10% lower lateral load than the predicted one, as shown in Fig.10. Based on the test data, explained in the next section, the lower lateral load was due to movement of inflection point along the columns. Ultimate drift of 24mm was obtained from the test data, which is perfectly about the predicted result. It was estimated by ASFI analysis-1 as 24mm and by ASFI analysis-2 as 28 mm. In the next sections, test data and analytical outcomes, considering movement of the inflections, are described.

4.1 Curvature and Movement of the Inflection Points

Test data indicted an ultimate lateral load 10% not only lower than the analysis of ASFI but also lower than AIJ flexural capacity. Afterward studies showed that this was due to inflection point movement of the columns. Caused by the loading system and height of the lateral load, columns of the frame experienced non-symmetric moment distribution along the height of each column. Even different curvature distribution was obtained for each column. It was found that inflection points in two columns were shifting related to lateral load and varying axial load during the test.

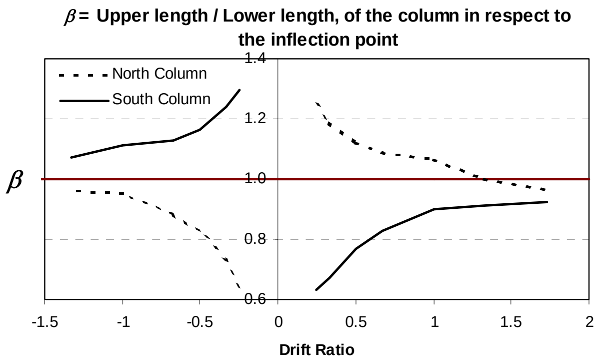

Fig.11 Movement of inflection point of the columns at different drift ratios

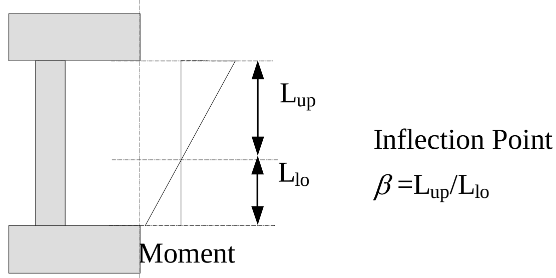

Fig.12 Parameter β in Fig. 11 and definition of inflection point

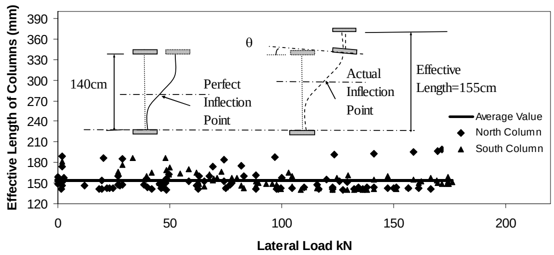

Fig.13 Computing the effective length of columns based on test data of straingages

Fig. 11 shows coefficient β, illustrated in Fig. 12, at each drift ratio for positive and negative directions of loading. It indicates that due to movement of inflection point, bottom end joints of both columns sustained higher moments than the top joints at 1.73% drift ratio when both columns failed in shear mode. Fig. 11 indicates that gradually as plastic hinges are formed, inflection points are shifting toward the mid-height of the columns. However, shear failure occurred before forming perfect plastic hinges. That is why stiffness and level of load estimated by analysis was higher than the test data by about 10% average. Therefore, in the analysis, capacity of the columns should be computed considering the movement of the inflection point. In order to do so, an effective length, which is the equivalent height of the column with inflection point in the middle height of the column as shown in Fig. 13, is computed based on the test data to apply in the analysis.

Average effective lengths of the columns were obtained, based on straingages data. First, curvatures for different sections of the columns were obtained based on strain distribution along the depth of each section, where strains were measured by straingages. Then inflection points are determined based on the curvature distribution along the columns. Hence, average effective length is computed equal to two times of the maximum length from inflection point to the ends, as shown in Fig. 13

4.2 Drift Ratio-Lateral Load Response and Comparison with the Analysis

Fig. 14 shows specimen RCF at drift ratio of 1.7% after shear failure.

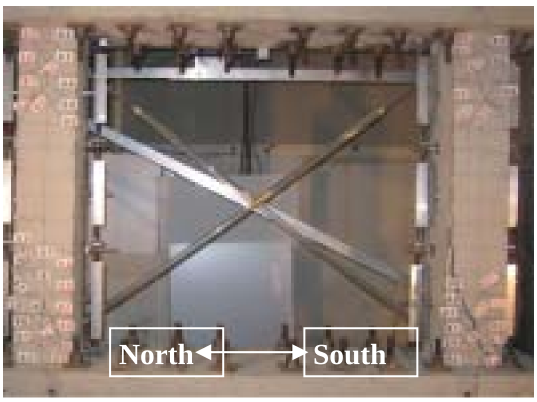

Fig.14 Specimen RCF after shear failure drift ratio of 1.7%

In order to obtain analytical response of the frame by ASFI method considering the movement of the inflection point, analysis was carried out for each column considering the varying axial load and varying effective lengths obtained from the test data in Fig. 11. The outcomes of the analyses are shown in Fig. 15 and Fig. 17. Furthermore experimental and analytical results for drift ratio-axial strain of both columns are presented in Fig. 16 and Fig. 18. Axial strain is determined based on axial displacement, measured by VS-5 and VN-5 in Fig. 3, divided by the length of the column. At the start point of loading with zero lateral load, equal axial loads are applied on both columns. However, as lateral load increases, axial load in north column is decreased and in south column is increased. Therefore, different performances are expected for the two columns due to different axial loads.

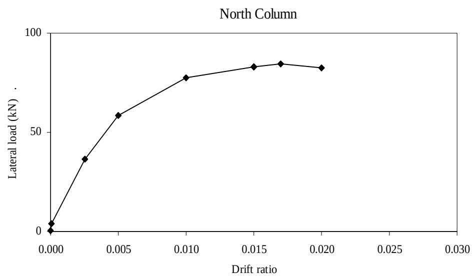

Fig.15 Analytical results by ASFI considering varying effective length for north column

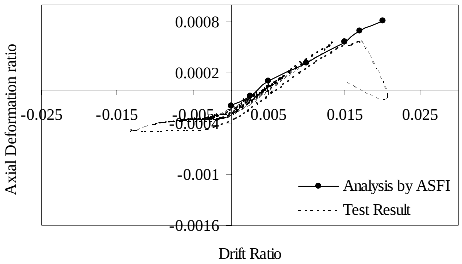

Fig.16 Comparisons between analytical and experimental results of drift ratio-axial deformation ratio relationship for north column

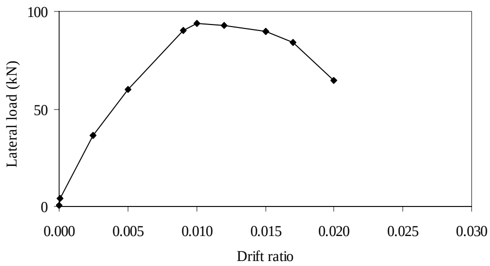

Fig.17 Analytical results by ASFI method considering varying effective length for south column

Fig. 15 shows the analytical results for north column with decreasing axial loads and Fig. 17 illustrates the results for south column with increasing axial load. Higher ultimate lateral load is obtained for south column with higher axial load and lower ultimate load is obtained for north column with lower axial load. Since, top and bottom stubs are almost rigid then total lateral load-drift response of the frame can be obtain as summation of lateral loads in Fig.15 and Fig. 17 at identical drifts. Fig. 19 shows analytical outcomes comparing with the experimental results.

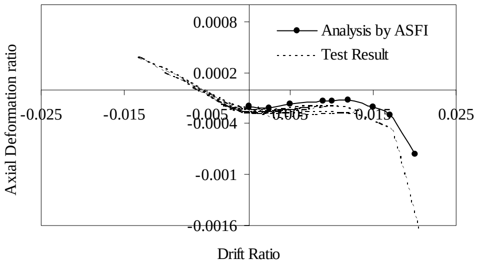

Fig.18 Comparisons between analytical and experimental results of drift ratio-axial deformation ratio for south column

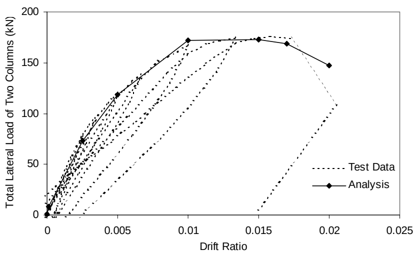

Fig.19 Comparison of test results and analysis by ASFI method by means of superposition of the analytical results for two columns

In different process, since average axial load of both columns is constant, considering the constant axial load, and constant effective length of 155 cm obtained in Fig. 13, analysis was carried out for one column and the lateral load results were multiply by two at each drift ratio, in order to obtain total response of the frame. Fig. 20 and 21 show the analytical results as well as experimental data. Both figures indicate that considering an average axial load gives a reasonable response for the frame.

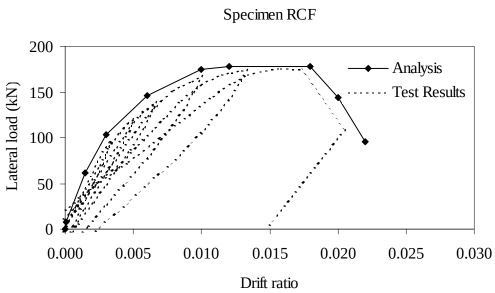

Fig.20 Comparison of the test results and the analysis by ASFI method considering the effective length of the columns

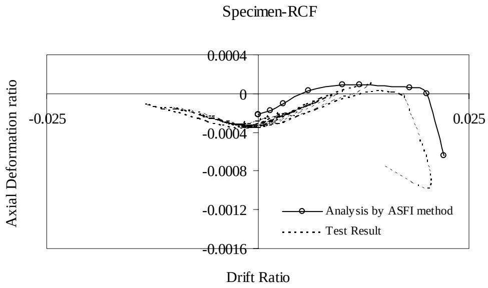

Fig.21 Comparisons between analytical and experimental results of drift ratio-average axial deformation ratio relationship for the two columns of specimen RCF

5. CONCLUSIONS

A reinforced concrete frame, consisting two columns, was tested, simulating a RC frame at the first-story of a building. Varying axial load related to lateral load was applied to the specimen. Performance of the frame was predicted by ACI and AIJ as shear failure before flexure. However, a flexure behavior followed by shear failure was estimated by ASFI method.

The results of the test showed clear flexure behavior. Due to the setup condition and the level of applied lateral load, based on the test data, inflection point was not recorded in the mid-height of the column. As the results higher level of lateral load capacity was estimated by ASFI method as well as AIJ-flexure equation. An effective length for the columns was obtained based on the test data and applied in the analysis. As the result, a proper correlation was achieved between the performance response estimated by ASFI method and the experimental outcomes.

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