# Truss Analysis for Evaluating the Behavior of Reinforced Concrete Moment-Resisting Frames with Poorly Reinforcing Details

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## ABSTRACT :

The target of the research in this paper is using truss analysis to predict the behavior of reinforced concrete moment-resisting frames, especially for the joints with poorly reinforcing details. The truss analysis is basically constructed by truss mechanism for a cracked RC frame. Parametric study for discussing concrete softened coefficients and joint shear degradation is included in this research. Furthermore, the truss model was verified by tested RC moment-resisting frames with different failure modes.

**KEYWORDS:** truss model, analysis, moment-resisting frame, beam-column joint

## 1. INTRODUCTION

Many analytical models for predicting inelastic behavior of reinforced concrete frames are developed in recent year. These analytical models can be used to analyze the nonlinear response of RC frames. However, these analytical tools are difficult to analyze the frames with poorly reinforcing details. Such as the frames typically constructed as Taiwan RC low-rise buildings which have many poor reinforcing details in base columns and beam-column joints. Generally, these analytical tools simulate the weak joints with poorly reinforcing details as rigid connections, and lead the deformation caused by the joint shear to underestimate. Therefore, the lattice model is chosen to analyze the RC moment-resisting frames with substandard reinforcing details in this research. This research has been cooperated with Professor Niwa and Prof. Miki from Tokyo Institute of Technology and Kobe University in Japan. The authors will use 3D lattice model which is created by Niwa and Miki to perform the analytical study on RC frames with poorly reinforcing details. Although the 3D lattice model is used for predicting the seismic behaviors of bridge piers originally, the analytical tool had be revised to analyze the moment resisting frames like Taiwan low-rise buildings and provided for a quick assessment and simple analysis.

## 2. ANALYTICAL MODEL

### *2.1. Structures of 3D lattice model*

The analytical model applied in this paper, which is called lattice model, is basically constructed by truss mechanism for a cracked RC frame. This model consists of concrete and reinforcement members as shown in Figure 1. The concrete members are modeled as many types of members, such as flexural compression, flexural tension, diagonal compression, diagonal tension, and arch members. Each member has different character and material property. For example, the role of diagonal member is to simulate the cracking behavior of the concrete. The arch member, which is located according to the direction of internal compression stress flow, represents the shear resisting mechanism. For the longitudinal and transverse reinforcements, they are modeled as horizontal and vertical members and represented as dashed lines in Figure 1.

### *2.2. Material Property for Concrete member*

There are many concrete models used for each different concrete member. For the compression members, the stress-strain relationship proposed by Mander et al. is applied to diagonal compression and arch members, Moreover, the stress-strain relationship described by Vecchio and Collins is applied to flexural compression members. On the other hand, for the tension members, the 1/4 model by Uchida et al. and tension stiffening curve proposed by Okamura and Maekawa are employed. For the concrete softened coefficient, the relationship proposed by Vecchio and Collins is applied to the concrete model here. For the hysteric rules of concrete, the cyclic stress-strain relationship proposed by Naganuma et al. is employed.

### *2.3. Material Property for reinforcement member*

The stress-strain relationship of reinforcing bars is regarded as bilinear in which the tangential stiffness after yielding is 1/100 $E_{s,}$ where $E_s$ is Young's modulus. The model proposed by Fukuura et al., used to address the Bauschinger effect, is applied for the cyclic stress-strain relationship of the reinforcement.

### *2.4. Modeling of each element*

Figure 2 shows the cross section of the analytical specimen, it can be observed that the cross section is divided into truss and arch parts. A value of t which is defined as a ratio that the width of arch part to width of full cross section is used. Consequently, the width of arch part and truss part are expressed as bt and b(1-t), which $0 < t < 1$. For the value of t, it is determined based on the minimization of the total potential energy theory. Here, the total potential energy can be obtained form the difference between the sum of strain energy of each element and external force. After the modeling and calculating, the stress and strain of each element can be calculated by structural matrix method.

## 3. PARAMETRIC STUDY

Originally, the 3D lattice model is used for predicting the seismic behaviors of bridge piers and columns before this study. In order to revise the lattice model to be appropriate for predicting the RC frames, some parameter and revision should be discussed in frame modeling. Such as choosing appropriate concrete softened coefficient for concrete member at beam-column joint. This research proposed that a suitable concrete softened coefficient for concrete member at joint is proposed by Belarbi and Hsu. Furthermore, according to previous research for predicting beam-column joint behavior at ultimate stage, the ratio of joint reinforcement restricted to the assumption of distributed joint reinforcement of the panel analysis has to properly reduce. The research suggested that the best reduced factor for the reinforcement ratio at joint is 0.6 for the interior joint of frames and 0.3 for the exterior joint. In this study, we adopt the conclusion of reduced factors for the reinforcement ratio in joints to truss analysis and got good result for predicting the cyclic behavior of moment-resisting frame.

## 4. EXPERIMENTAL VERIFICATION ON BASE-STORY FRAMES

### *4.1. Details of Test Unit*

The details of four tested frames with different failure modes were presented in Figure 3. Furthermore, the concept of design for each frame was described in the following:

Yang-JI: The frame was designed according to ACI 318-02, having close transverse reinforcement inside the column and joint.

Yang-J2: The specimen, which had no transverse reinforcement at the joint, was designed to fail in joint shear failure. The specimen represented the RC moment-resisting frame with poorly reinforcing details.

Yang-J3: The frame with poor transverse reinforcement in the base column was designed to column shear failure.

Yang-J4: The frame had both deficiencies similar to Yang-J2 and Yang-J3. The purpose of the design was to simulate the non-ductile RC frames with multiple failure modes in joint shear and column shear.

### *4.2. Comparison between experimental and analytical results*

For four tested specimens with different failure modes, the predicted results by lattice model are represented in Figures 4 to 8. Moreover, the detailed descriptions are expressed as the following sections.

#### *4.2.1 Overall behavior*

Figure 4 shows the lateral force versus lateral displacement of the four tested specimens. It can be observed that the predicted results analyzed by lattice model agree with the measured response. In these tested units, the unit Yang-J1 shows a good performance and ductility as shown in Figure 4(a) because it was designed according to the ACI code. The unit Yang-J2, which has no transverse reinforcements in the joint, similar to Yang-J1 case, represents a good analytical result in overall response; see Figure 4(b). Figure 4(c) shows the predicted result of the unit Yang-J3. The specimen, with poorly reinforcing in the column, is another type of failure mode different from the unit Yang-J2. The predicted and measured lateral forces-displacement relationships are also matched because they degraded at the similar point which the maximum lateral force reached 185kN and the displacement was about 65 mm. For the unit Yang-J4 having multiple failure modes, it is the most difficult specimen to model in the Yang-series. Figure 4(d) indicates that the predicted response is coincided with the measured response because the hysterias loops started degrading at the same lateral force and displacement.

From the previous analyses, the results indicate that the lattice model can predict these types of failure mode very well.

#### *4.2.2 Detailed analysis*

More detailed analyses in concrete and reinforcement in joints and columns are discussed in this section The detailed analyses include the shear stress and shear strain analyses in joint and column, and the strain of the reinforcement at beam and column ends. The results are described in the following paragraph.

The comparisons for the shear stress versus shear strain in joint between predicted and measured results were depicted in Figure 5. In Figure 5(a), 5(c) and 5(d), although the predicted joint shear stresses are less than measured values, the predicted joint shear strains had a good agreement with experimental response.

On the other hand, the lateral forces versus shear strains in column of Yang-series units are represented in Figure 6. It can be observed that the tendency of the predicted column shear force coincides with the measured values well. However, from the units Yang-J2 and Yang-J3 (see Figures 6(b) and 6(c)), the column shear strain of these two specimens did not predict well. This result indicates that it is difficult to predict the deformation at shear failure with a feasible accuracy.

The strains of reinforcement at the beam ends near the joint are depicted in Figure 7. It can be found that the predicted and measured values for units Yang-J1 (see Figure 7(a)) are matched because the reinforcement strains started yielding at 3% drift ratio. In the unit Yang-J2 (see Figure 7(b)), the tendency for predicted and measured curves also show close between two curve. For the units Yang-J3 and Yang-J4, the measurements show that the reinforcement strain of the beam reach yielding strain at 1% drift ratio but the predicted response did not. It might be the reason that the bars slip effect was overestimated during analyzing. That will cause the reinforcement strain of the beam can’t yield. This issue, such as improvement of the slip relationship, should be discussed in the future.

For the reinforcement strain at the column base, the comparison between predicted and tested result are depicted in Figure 8. It can be observed that the predicted and measured column responses have a better agreement than beams.

## 5. CONCLUSION

At this moment, the modified lattice model can predict the overall response of moment-resisting frames well. However, from the detailed comparison between analytical and experimental results, reinforcement strain prediction on the column seemed better than that on the beam. The reason for the beam prediction with less accuracy could be in the joint modeling, which is originally proposed by Wang. That means the idea for reducing beam bar area to simulate joint shear behavior should be amended in the future.

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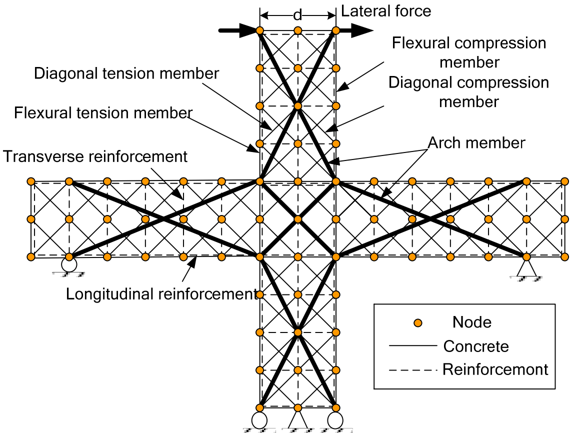

Figure 1 Outline of the lattice model

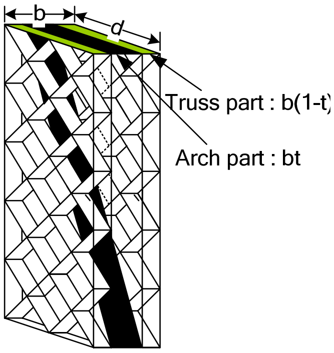

Figure 2 Cross section of RC column model

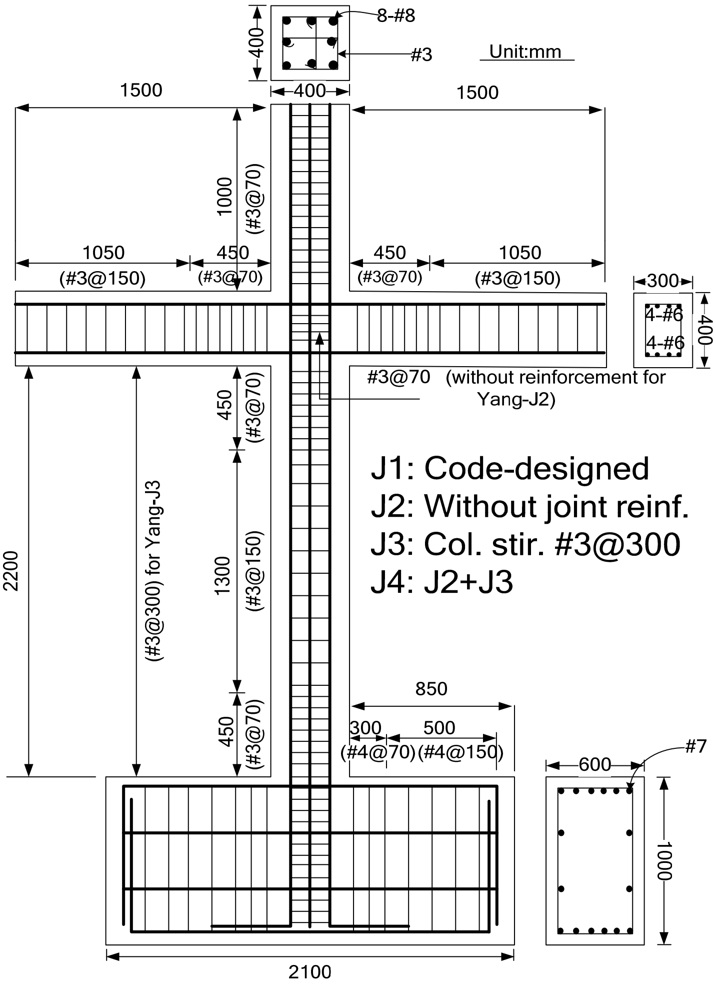

Figure 3 Detail of Yang-series

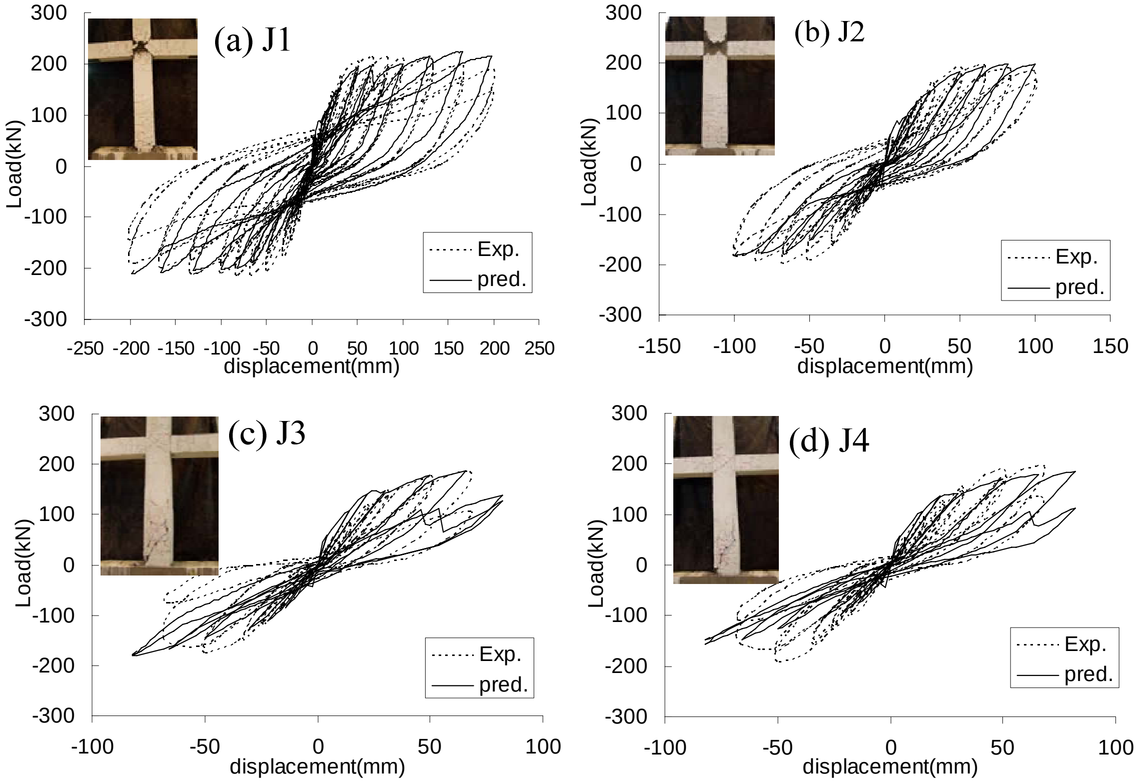

Figure 4 Overall behavior of Yang-series

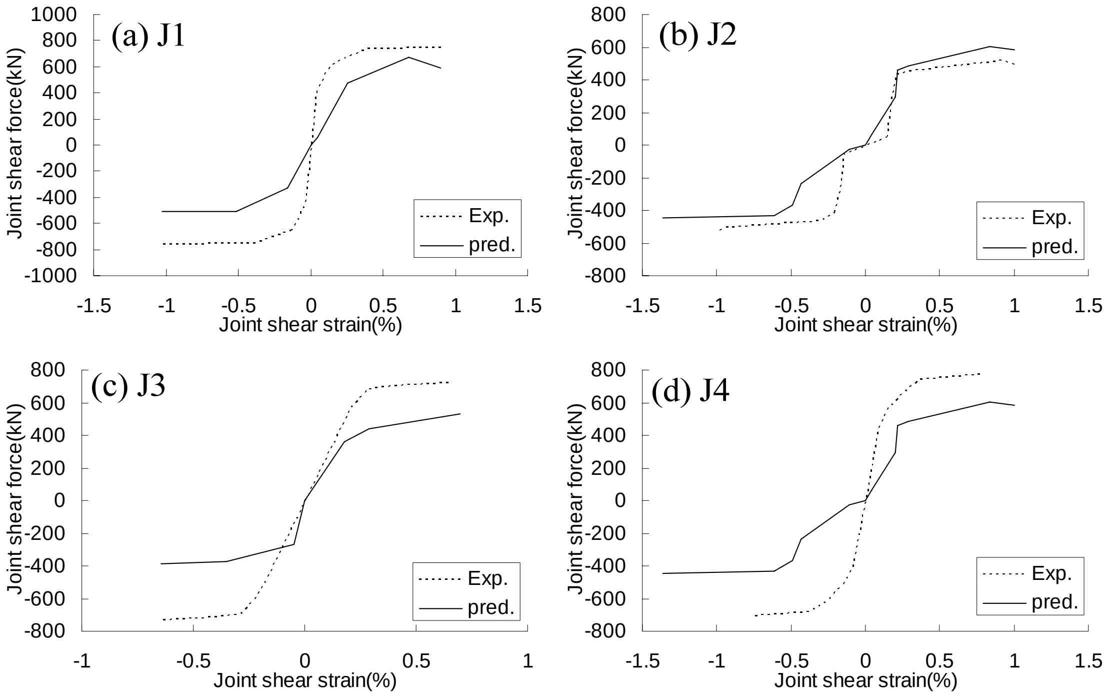

Figure 5 Joint shear force versus joint shear strain of four units

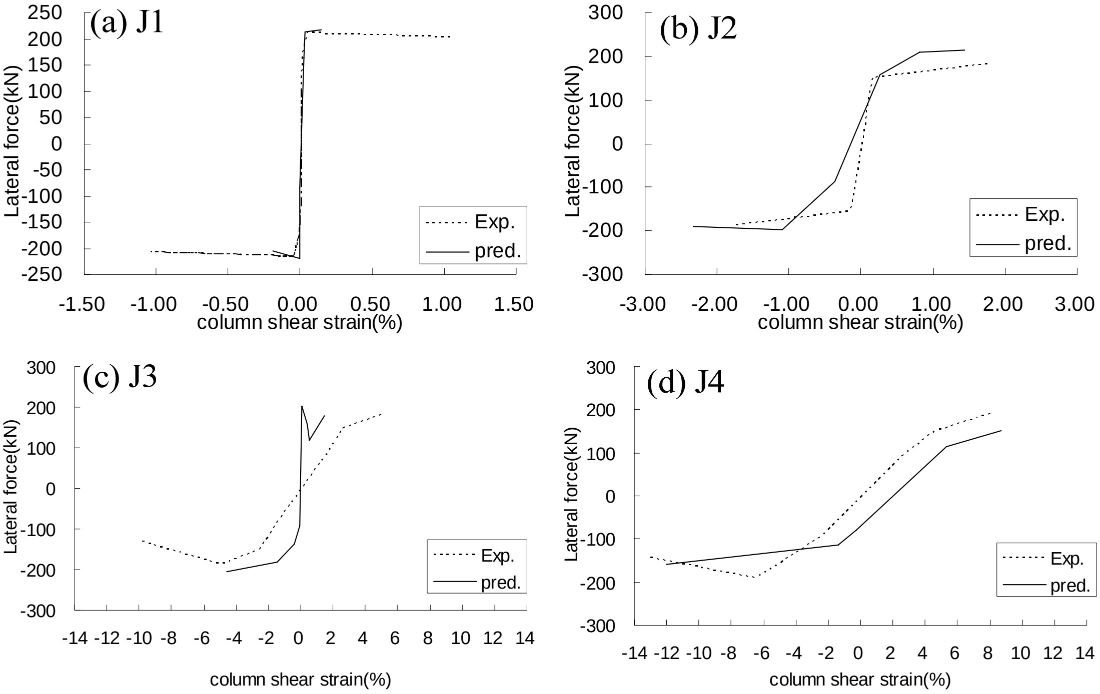

Figure 6 Force versus column shear strain of four units

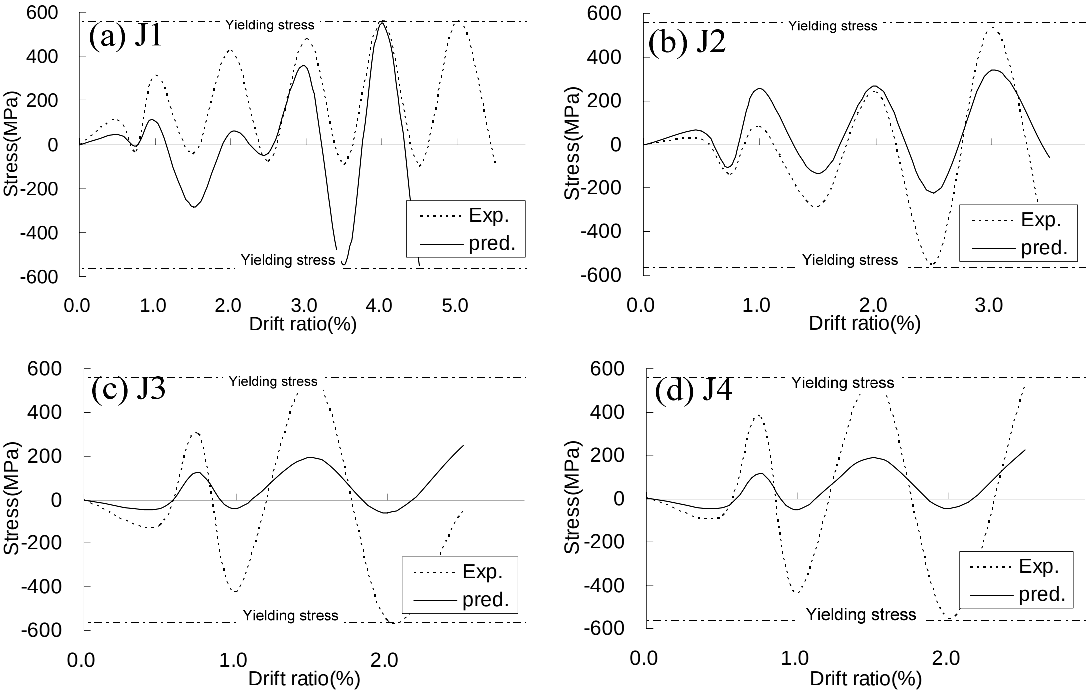

Figure 7 Reinforcement strain of beam

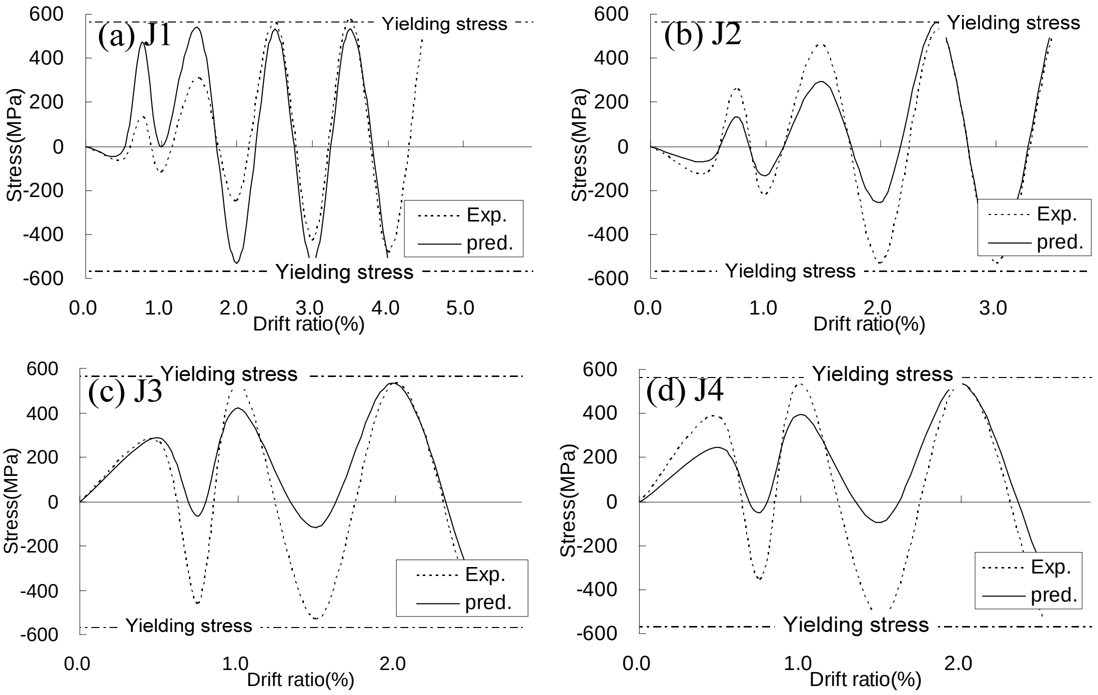

Figure 8 Reinforcement strain of column