論文 The Analysis of Localized Failure of Reinforced Concrete Shear Wall

Guo-xiong YU*[1] and Tada-aki TANABE*[2]

ABSTRACT: The shear band localization phenomenon can often be observed from the experimental results of R.C. shear wall. There are no theoretical explanations or numerical simulations to explain this phenomenon in the past. In this paper, through numerical analysis, it shows that this phenomenon is caused by the material instability when the material acoustic tensor ceases to be positive. Also, example is given to show how the analytical results is affected when the shear band localization is taken into account.
KEYWORDS: reinforced concrete, shear wall, shear band localization.

1. INTRODUCTION

For the localization problem related with losing positive definiteness of the acoustic tensor, quite extensive papers have been published in the past in regards to the materials of metal, pure concrete, rock and soil, etc. However, no paper has appeared to analyze the shear band localization phenomenon in reinforced concrete.

Experiments showed that the localized shear band did occur in shear wall structures. For these structures, the shear bands occurred along the directions which were entirely different from the initially formed crack directions. Although all the researchers who conducted the experiments and observed this failure mode considered that it is due to sliding shear failure of concrete, the mechanism, the driving force behind this localized shear band failure remains unclear up to now. Frequent occurrence of this localized failure mode and its specific appearance let the authors feel strongly that there should be some relation between this localized failure mode and the localization instability of material and it was worthwhile giving effort to make investigation on it from a new angle of view.

In this paper, first, both the experiment in R.C. panel and R.C. shear wall structures will be scrutinized to show the shear band localization phenomenon did exists in experiments and under what condition the shear band localization phenomenon would occur, and then, numerical analysis will be given to explain the localization phenomenon in R.C. panel and to simulate the localization phenomenon in R.C. shear wall structures.

Different from the past researches by other authors in respect to localization in which the analytical objects were pure material, in this paper, the R.C. shear wall is taken to be a composite material. The model for R.C. panel developed at Nagoya University [1] is used in this paper. In the analysis of the reinforced shear wall structure, the finite element method with localized zone embedded [2] is used.

*1 Department of Civil Engineering, Nagoya University ,Member of JCI
*2 Department of Civil Engineering, Nagoya University, DR,Member of JCI

2. Experimental Observations of the Failure Modes of the Reinforced Concrete Panel

Several experiments have been carried out in the studying of the behavior of R.C. panels. These include the one by Vecchio and Collins [3] and Tsubota [4], etc.

According to the experimental reports, the ultimate failures of the tested panels often involved one of the following two distinguished modes:

1. Yielding of either the longitudinal or transverse steel (Mode I, **Fig.**1 (a)).
2. Sliding shear failure of the concrete prior to yielding of either the longitudinal or transverse steel (Mode II, **Fig.**1 (b)).
3. Preliminary pull out failure due to the imperfection or the stress concentration on the edge of the specimen.

In the case of Mode I, the damage occurred in dispersing way, while in case of Mode II, the damage occurred in concentrating way with a localized band seen.

It was observed in Vecchio and Collins' test that, for both failure Mode I or Mode II, the initial cracks formed at 45° to the reinforcement grid, at shear stresses ranging from $0.3\sqrt{f_c'}MPa$ to $0.5\sqrt{f_c'}MPa$. As the load increased, the number and average width of the initially formed cracks also increased. The crack direction did not change, until ultimately, "true" failure of either Mode I or Mode II occurred. For Mode I, the ultimate failure occurred with the initial crack becoming wider and wider and finally the panel failed with the yielding of the reinforcement, but the damage seemed not so localized. But for Mode II, the ultimate failure occurred with a shear band formed in the direction entirely different from the initial crack direction, and this shear band always formed almost parallel to one of the edge of the specimen.

In Vecchio and Collins' experiment, there were 26 specimens which had been tested under two-dimensional stress states. There were 6 specimens which had the failure Mode II (PV9, PV22, PV27, PV23, PV24, PV25), and 15 specimens which had the failure Mode I, the other specimens failed prematurely due to "pull-out" of the shear keys.

(a) (b)

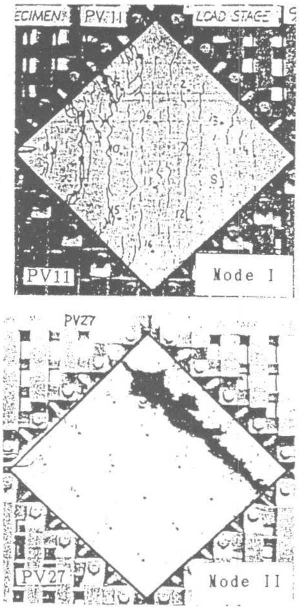

Figure 1: Failure Mode by Experiments

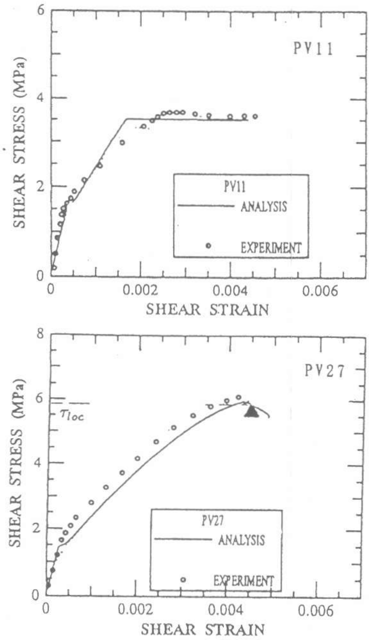

Figure 2: Comparison Between Experiment Results with Analytical Results

By examinations of the experimental data of not only Vecchio and Collins but also Tsubota and others, it can be known that the Mode I was caused by the yielding of the reinforcement when the specimen was so made that at least one of the reinforcement ratio was small or the reinforcement strength was relatively low. On the other hand, when the reinforcement ratio or the reinforcement strength was relatively high or the concrete strength

Table 1: The Angle of the Localization Vector α_n

Specimen	PV10	PV11	PV22	PV23	PV24	PV27
α_n (analysis 2)	*	*	85.47°	83.30°	89.03°	90.00°
Experimental Result	*	*	90°	90°	90°	90°

* means no localization has been detected.

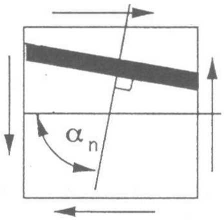

Figure 3: The Angle of α_n

was low, the Mode II would possibly occur. Furthermore, when the specimen was under the combined stress state of compression and shear, the Mode II was possibly triggered. In Vecchio and Collins' experiment, when the concrete has high strength and with strong reinforcement (the reinforcement ratio or the reinforcement strength is high), it often resulted in "pull-out" failure. Also, the same conclusion can be made by examining the experiments by other researchers.

3. Analysis of the Localization Failure Modes and Comparison with the Experimental Results

As it is known, there are two reasons that will cause the localization phenomenon, one is the loss of the positive definiteness of the tangential constitutive matrix, and the other is the loss of positive definiteness of the acoustic tensor. If this phenomenon of Mode II was caused by the loss of the definiteness of the tangential constitutive matrix, the localized zone should be in the same direction as that of the previously formed crack which was perpendicular to the principle tension stress. However, what actually happened in the experiments for the specimens with failure Mode II was that, the localization band was in quite different angle with the previously formed crack. The localization failure Mode II should be caused by the loss of positive definiteness of the acoustic tensor.

The shear band localization condition [5] can be expressed as

$$det(\mathbf{A}(\mathbf{n})) = 0 \tag{1}$$

where $A_{jk}(\mathbf{n}) = (n_i D_{ijkl} n_l)$ is the acoustic tensor and D_{ijkl} is the tangential constitutive matrix for the composite material composed of concrete and reinforcement mesh. The localization will be triggered by the satisfaction of Eq.(1). In evaluating Eq.(1), the proper choice of good constitutive model looks very important since occurrence of zero value depends on the model. Here, the tangential constitutive matrix $\mathbf{D}$ is according to the Nagoya University model [1].

The analysis of this section was on constitutive level in which the increment of the strain was calculated according to the stress increment and the tangential constitutive matrix. In the process to obtain the stress-strain curve for specimens, the localization condition of Eq.(1) was analyzed in every stress increment to see whether this localization condition was satisfied or not. As the analysis of this section is in constitutive level, it should be reminded that constitutive equation in its fundamental formation does not predict localization location.

The angle between the vector $\mathbf{n}$ and the x axis, α_n (**Fig.**3), is shown on **Tab.**1 for every specimen compared with the experimentally obtained angles. For the specimen with Mode I, no occurrence of localization was predicted, while for the specimen with Mode II, the localization occurrence at some distance after the peak point where the compressive deterioration of the cracked concrete began was predicted. Moreover, when localization is predicted, the predicted localization vector $\mathbf{n}$ was almost perpendicular to one of the edge of the specimen, which were in good agreement with the experimental results.

Fig.2 shows the shear stress and the shear strain relation of specimens PV11 and PV27 obtained both by analysis and compared with the experimental results. The point at which the localization occurred is pointed by marking "▲". The results of the other specimens with failure Mode II are similar to these of specimen PV27.

By numerical analysis, the failure Mode II is proven to be a shear band localization phenomenon.

4. Experimental Observations of the Localization Phenomenon in Reinforced Concrete Shear Wall

Experiments show that the shear band localization phenomenon did exist in R.C. shear wall structure, for examples, the experiments tested by Saatcioglu [6] and Hirosawa [7], etc.

In Saatcioglu's tests, there were two specimens tested, Wall 1 and Wall 2. **Fig.**4 illustrates the overall geometric properties of the specimen tested in the experiment. **Tab.**2 provides a summary of this two specimens. Wall 1 was designed to have less reinforcement in the horizontal direction so the shear capacity was lower than the flexural strength. Wall 2 was designed to have higher shear capacities.

For Wall 1, at first, the dispersed crack occurred, and then near the peak point, diagonal cracks formed, and finally the longitudinal reinforcement yielded. Although the major diagonal crack had formed, the other part of the structure had also undergone serious damage. Damage seemed not so strongly localized. **Fig.**5(a) shows the crack and the damage pattern of the Wall 1.

Here, the term "Mode I" will still be adopted to describe the failure mode in which the damage is not strongly localized but rather in distributed crack pattern, and the term "Mode II" will be referred to the failure mode shown next.

For Wall 2, before the peak point, like Wall 1, the diagonal tension cracks occurred, but the reinforcement did not yield. As the load increased, the sliding of the wall along the foundation started when the shear band formed. A significant drop in the load resistance was recorded as the wall slid to imposed deformation level. **Fig.**5(b) shows the crack and damage pattern of the Wall 2 at the end of the testing. **Fig.**6 shows the force-deformation relationship curve and the force-sliding relationship curve. It is clear from **Fig.**6 that a large portion of lateral deflection was due to the shear-sliding while in Wall 1 the sliding was insignificant. The remaining part of the specimen did not suffer any further damage, while it underwent in the shear-sliding mode, or in other word, large strain localized into this sliding shear band and led the structure to failure without affecting the remaining part of the structure .

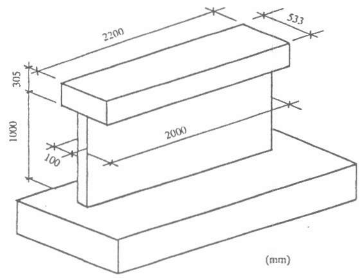

Figure 4: The Dimension of the Shear Wall

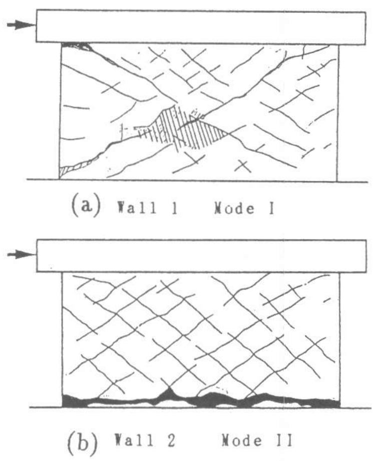

Figure 5: The Crack and the Damage Patterns

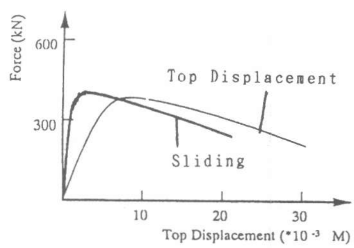

Figure 6: Force and Displacement Relation for Wall 2

Table 2: Properties of Test Specimens by Saatcioglu

		V. Reinf.	V. Reinf.	H. Reinf.	H. Reinf.	
Specimen	f_c' (MPa)	f_y (MPa)	$\rho(\%)$	f_y (MPa)	$\rho(\%)$	Failure Mode
Wall 1	25	435	0.8	425	0.25	I
Wall 2	33	480	0.8	480	0.8	II

V.— Vertical direction.
H.— Horizontal direction.

5. Localization Analysis of the Reinforced Concrete Shear Wall

In the following, we will analyze the Wall 2 by taking the shear band localization phenomenon into consideration. The finite element with embedded discontinuous strain field [2] (the embedded localized band width is taken as $4d_a$, where d_a= maximum size of aggregate in concrete) will be used in the elements where the localization are detected, and the analytical results will be compared with those of experiments.

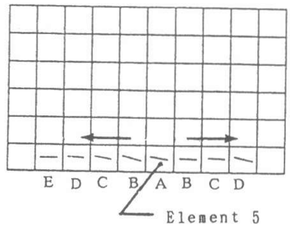

Figure 7: Element and Step in Which the Localization Occurs

Fig.7 shows the finite element mesh. The material properties of the shear wall used in this analysis are listed in **Tab.**2.

Fig.8 shows the relationship of the force and the displacement at the top of the shear wall obtained with and without considering the localization phenomenon.

As shown by **Fig.**8, at step A, the shear band localization firstly occurred at the No.5 element. After adding the localization deformation modes to the No.5 element, the response of the structure was forced to go to the other bifurcation path differing from the original one. It is clear that, for the element with embedded localization modes, less stress is needed than that for the general element to produce the same strain. So, when the localization modes were added to the No.5 element, the stress would decrease in the No.5 element. Consequently, the stress of the element besides to the No.5 element would increase. As a result, after the shear band localization occurring in the element of No.5, the shear band localization would occur in the element in the two sides of the No.5 element . **Fig.**7 shows the elements and the step in which the localization occurred. The arrows show the directions of the development of the shear band. The steps are depicted in **Fig.**8.

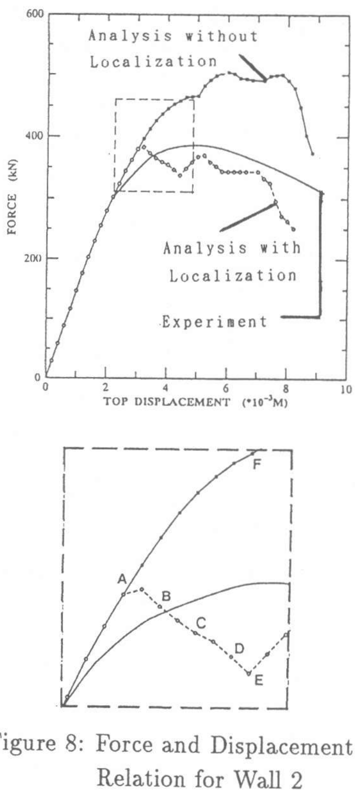

Figure 8: Force and Displacement Relation for Wall 2

Fig.9(a) shows the deformed mesh at step E resulted by the analysis with embedded localization zone method, while **Fig.**9(b) shows the deformed mesh at step F resulted by the analysis without localization consideration. **Fig.**9(c) shows the deformed mesh at step A by the both methods. From **Fig.**9(a), we can see that the displacement of the top beam of the shear wall was due to the shear sliding of the shear band which value is shown in **Fig.**10, and the strain was localized into the shear band while the other portion of the shear wall experienced little deformation.

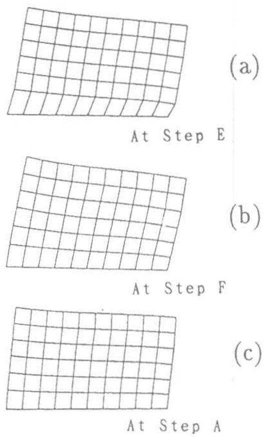

Figure 9: Deformed Mesh

6. Conclusion

In this paper, two kinds of failure modes of R.C. panel and shear wall structures have been described. The finite element with embedded localization zone has been used to simulate the shear band localization behaviors of the R.C. shear wall. Through numerical analysis and the comparison with experimental observations, it can be concluded that:

1. When R.C. panel and R.C. shear wall structure are strongly reinforced, the shear band localization phenomenon probably occur. The failure Mode II is caused by the shear band localization instability.
2. When the general method (without considering the shear band localization) is used to analyze the shear wall with failure Mode II, the maximum resistance force is found to be considerably larger than that obtained by the experiment. The localization analysis as shown above seems to provide a way to obtain the correct results and to explain the true mechanism of the shear failure mode of R.C. wall.

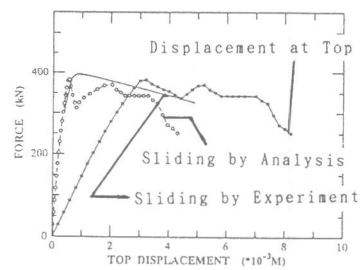

Figure 10: Sliding of the Wall 2

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