論文 Role of Transverse Reinforcement on Ductility and Failure Mode of RC Bridge Piers Subject to Earthquake Motion

Khairy Hassan **ABDELKAREEM** *1　　**MACHIDA** Atsuhiko *2

ABSTRACT: The role of shear reinforcement on ductility level of RC bridge piers is focused using nonlinear 3D finite element analysis. Inelastic responses are obtained leading to good understanding for the effect of shear reinforcement on ductility levels and failure modes of the piers. Increasing transverse steel to a certain level leads to change of failure mode from severe diagonal shear cracking to flexural cracking. The optimum ratios of shear reinforcement are obtained taking into account the effect of axial load, percentage of main reinforcement and ratio of the height relative to the width. At the level of the recommended ratios, diagonal shear failure does not control the behavior of piers.
KEYWORDS: inelastic response, dynamic analysis, nonlinear 3D finite element analysis, ductility, bridge piers, shear failure mechanism, transverse reinforcement, optimum shear reinforcement ratio.

1. INTRODUCTION

In the seismic design of RC bridge piers, the regions of maximum straining actions, which are called the potential plastic hinge regions of the piers, need to be carefully detailed for enough ductility in order to ensure that strong earthquakes will not cause severe collapse. The most important design considerations for ductility of bridge piers is the provision of sufficient transverse reinforcement in order to prevent shear failure, confine the concrete and to prevent buckling of longitudinal bars. As demonstrated by the collapse of concrete structures at several sites of highway and railway during the Great Hanshin earthquake in January 17,1995 (1), many of our concrete structures did not have sufficient strength and ductility to resist strong ground shaking. Moreover, due to this destructive earthquake, much damage occurred and the piers of bridges suffered mainly diagonal shear failure mechanism. This severe failure mode was mainly due to lack of shear reinforcement. An accurate estimation of ductility in structural and sectional levels is very important. In this study, a developed 3D finite element model taking into account the influence of these factors is utilized and based on the results of the analysis, the shear failure mechanism and ductility behaviors are discussed taking into account the effect of shear reinforcement ratio, main reinforcement ratio, pier size and axial compressive stress level.

2. MODELING

Suppose we have a RC bridge pier of square or rectangular cross section of dimension (h x b) which is assumed to be of constant value for each studied case. Fig. 1 illustrates the model and the

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*1 Doctoral Student, Dept. of Civil and Environmental Engineering, Saitama University.
*2 Professor, Dept. of Civil and Environmental Engineering, Saitama University.

parameters of the analysis. Main reinforcement ratio is changed to be 0.85 and 1.2 and height of the pier (L) is varied to give (L/h) as 2, 3, 3.75, and 4.5. Also, the percentage of shear reinforcement is changed as 0.1, 0.15, 0.25, 0.35, 0.45, 0.55 and 0.65 % to study the effect of shear reinforcement on improvement of ductility of such structures. Percentage of shear reinforcement is expressed as (A_{sh} / e.h) in which; (A_{sh}) is the area of cross section of hoop bar, (h) is the width of the pier cross section and (**e**) is the spacing between the transverse hoops. Top of the pier is subject to axial compressive load of constant value for each case. Axial compressive stress level is taken as $\frac{P}{A_c F_c'}$ where **P** is the concentrated load at top, F_c' is the compressive strength of concrete, and A_c is the gross area of concrete cross section. The axial compressive stress levels used in the analysis are: 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4 and 0.5. The super deck of the bridge is represented by a concentrated mass at the top of pier with assumption of lumped mass of the pier. Each pier is subjected to the scaled El Centro earthquake acceleration wave to be of peak acceleration of approximately 0.8 g as large as Hanshin wave. In this study, only the horizontal wave is used, and in another study the authors tend to make analysis related to effect of including vertical motion which was strong in Hanshin earthquake. A three dimensional finite element technique is used to carry out inelastic time history response analysis from which the role of shear reinforcement on behavior of bridge piers is demonstrated. The constitutive equations required for modeling both of concrete and steel are installed taking into account the nonlinearity of materials due to effect of cracking and strain softening of concrete (2,3,4,5,6). The nonlinear equation of motion is solved numerically using the nonlinear incremental Newmark-Beta operator (7, 8).

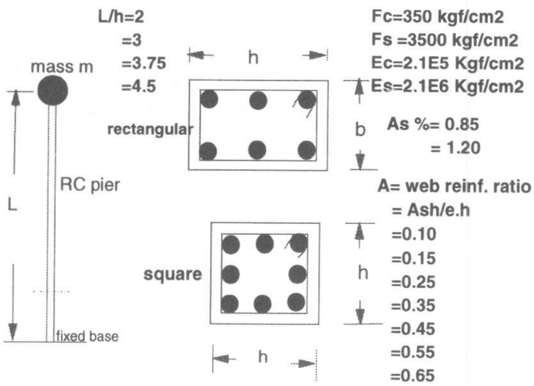

Fig. 1 Parameters and model of study

3. SHEAR REINFORCEMENT AND DUCTILITY OF PIERS

From the analysis of the obtained results, we calculate the displacement ductility factor for the piers with different percentages of shear and main reinforcement, pier sizes and axial compressive stress levels. The displacement ductility factor is calculated as (9, 10, and 11):

$$D.F = \frac{\Delta_u}{\Delta_y} \tag{1}$$

in which; Δ_u is the displacement corresponding to 0.8 of the maximum carrying load capacity of the pier, and Δ_y is the maximum displacement corresponding to the first yield of longitudinal steel. If the carrying load reaches 0.8 of the maximum value, then considerable reduction of the strength of piers occurs and we can assume that the pier is collapsed. Fig. 2 illustrates the method of determination of ultimate and yield displacements from both displacement and shearing force capacity responses as it is shown in the shearing force response with the corresponding displacement response in the figure. The accuracy of the obtained results of ductility depends upon the definition of ultimate displacement because there is no unique value for ultimate displacement of concrete and it differs from the researcher to another. The reader may refer to the references (9, 10, and 11) for more details.

Fig. 3 illustrates the relations between percentage of shear reinforcement and displacement ductility factor for different axial compressive stress levels. It is clear that as shear reinforcement increases, ductility factor increases significantly. Shear reinforcement confines the concrete core resulting in higher concrete strength. Also, shear reinforcement carries a part of shear stresses as well as it increases the shear resistance of concrete by improving its ultimate compressive strength. Also, it is clear from the figure that for higher axial compressive stress levels, the role of shear reinforcement becomes more significant than that in case of lower axial stresses. This is clear from the relatively high rate of increase of ductility factor for axial stress levels of 0.3 or more and smaller rate of increase when axial compressive stress is 0.1 or 0.2. This is because for lightly loaded columns, the role of confining reinforcement is not so significant For higher axial stresses, the induced lateral strains are high and consequently the required quantity of shear reinforcement for the purpose of confinement becomes higher. From this, the authors conclude that for higher axial compressive stresses, bigger quantity of shear reinforcement is needed to provide enough ductility for the piers. The shown curves can be represented by the following linear equation :

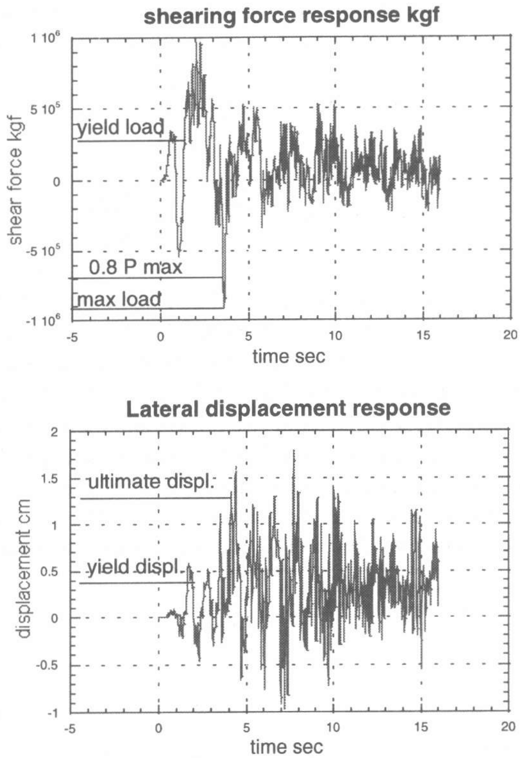

Fig. 2 determination of ultimate and yield displacement from displacement and force capacity responses of RC pier.

$$D.F = A1 + B1*(A_{sh}) \quad (2)$$

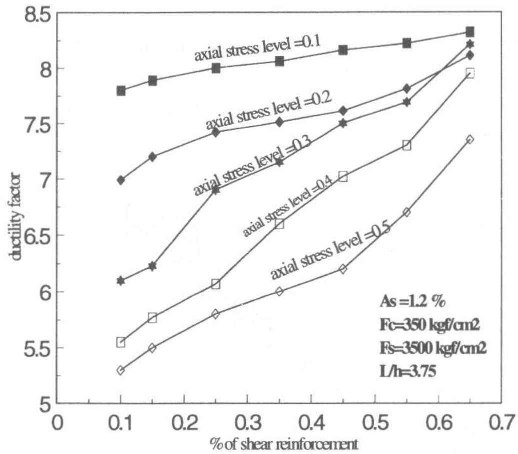

Fig. 3 effect of shear steel on ductility of RC piers.

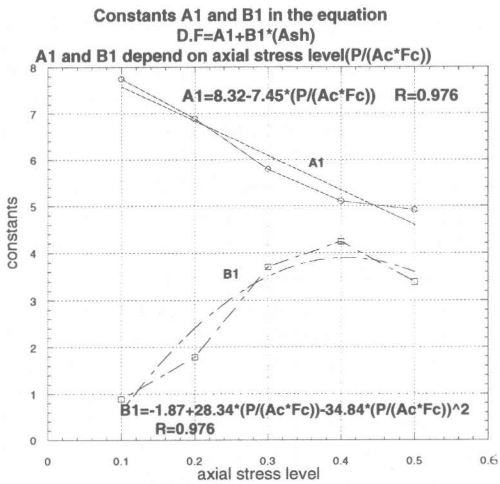

Fig. 4 determination of constants of Eq. 2

where, A1 and B1 are constants depending on axial compressive stress level and can be obtained from suitable regression of the results as it is illustrated in Fig. 4 with the following relations:

$$A1 = 8.32 - 7.45 * \frac{P}{A_c F_c^{\prime}} \quad (3)$$

$$B1 = -1.87 + 28.34 * (\frac{P}{A_c * F_c^{\prime}}) - 34.0 * (\frac{P}{A_c * F_c^{\prime}})^2 \quad (4)$$

Fig. 5 (A and B) illustrates the relation between shear reinforcement ratio and ductility factor for piers having different values of **L/h** ratio (L/h=2,3,3.75 and 4.5) for two cases of axial stress levels (0.12 and 0.3). It is necessary to mention that Fig. 5 shows the interaction between $A_{sh}\%$ and L/h ratio and their role on ductility level under constant axial stress, whereas Fig. 3 shows the interaction between $A_{sh}\%$ and axial stress level and their role on ductility level of piers under constant **L/h** ratio. From Fig. 5, we see that bigger ratios of shear reinforcement are needed for piers having smaller L/h ratios especially for higher levels of axial stress. This is because for small pier heights, shear effect is dominant and in case of bigger pier heights, flexural stresses are more effective. However, it can be shown that the effect of (L/h) ratio is small compared to the effect of axial stress level.

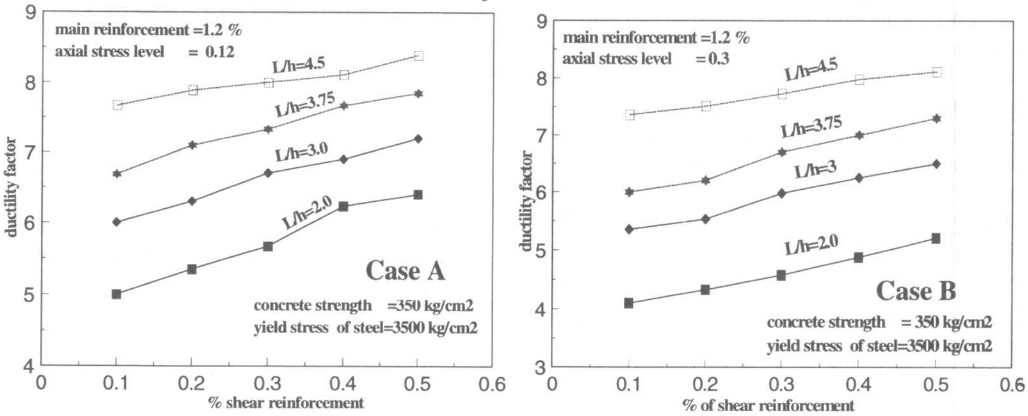

Fig. 5 (A and B) effect of pier size on ductility of RC piers with different shear reinforcement ratios.

From regression of the results, equation 5 is obtained to estimate the ductility levels of RC piers subject to earthquake motions taking into account the effect of shear reinforcement, axial stress level, pier size and ratio of main reinforcement. It is clear from the equation that the influence of both the axial stress level and ratio of shear reinforcement ratio on ductility is significant however the effect of main reinforcement ratio is not so large. Fig. 6 illustrates the regression and the accuracy of the given equation. As a conclusion, ductility of RC bridge piers depends on the quantity of shear reinforcement, axial compressive stress level, pier height relative to pier width and main reinforcement ratio. As axial stress level is high, height of the pier relative to its width is small and main steel ratio is small then bigger quantity of shear reinforcement is needed to maintain the ductility level. The obtained equation is as follows:

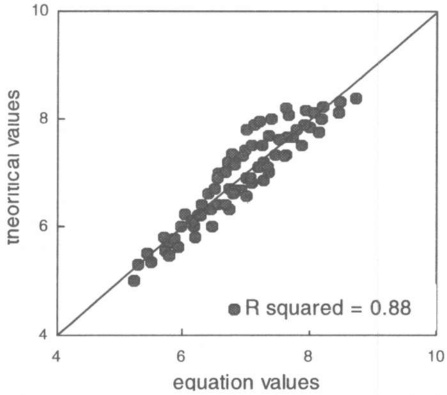

Fig. 6 Regression and accuracy of Eq. 5

$$D.F = 2.79 + 2.7 * (A_{sh}) - 4.24 * \left(\frac{P}{A_c.F_c^{'}} \right) + 0.97 * \left(\frac{L}{h} \right) + 1.03 * (A_s) \qquad (5)$$

It is clear from the equation that ductility of piers increases with the increase of main reinforcement however this is slightly different from the previous experimental results and hence further studies are needed to clarify this point although the effect of main steel is very small. Also, it is necessary to mention that the given equation is based on theoretical results using only the scaled El Centro earthquake motion, so further studies are needed to clarify the effect of motion types on the ductility level of piers. Also, the equation should be verified using experimental studies. These necessary points are now under consideration by the authors and the results will be published.

5. FAILURE MODE OF RC BRIDGE PIERS

In our analysis both of lateral plastic strain and principle plastic strain are taken as damage indices for concrete subject to cyclic loading from earthquake waves (12 and 13). The rate of change of plastic strain depends on the percentage of shear reinforcement, main reinforcement ratio, and axial compressive stress level. It is found that as ratio of transverse reinforcement increases, the magnitude and sign of lateral plastic strain change significantly. Fig. 7 illustrates the induced lateral plastic strain at positions of collapsed concrete of RC square pier having two different ratios of shear reinforcement (0.1 and 0.3). When the ratio is 0.1 %, diagonal shear collapse occurs . This can be shown by the sign of plastic strain which is tensile. However, flexural collapse near the base of the pier occurs when shear steel ratio is increased to 0.3%. At that ratio, compressive plastic strain is obtained. Increasing shear reinforcement from 0.1 to 0.3 % leads to change of sign of plastic strain from pure tensile (diagonal shear failure) to pure compression. From the observation of distribution of plastic strains, we are able to determine the ratio of shear reinforcement at which failure mode changes from diagonal to flexural or when diagonal cracking does not become significant and we call this ratio as optimum one. Fig. 8 illustrates the idea of determination of the optimum shear reinforcement ratios. As shear reinforcement ratio increases, the induced lateral tensile plastic strain at position of diagonal cracking decreases significantly till a certain ratio at which diagonal collapse does not occur. At this level, the compressive plastic strain near the base of the pier increases significantly and failure mode changes from diagonal cracking to flexural one. Table 1 summarizes the

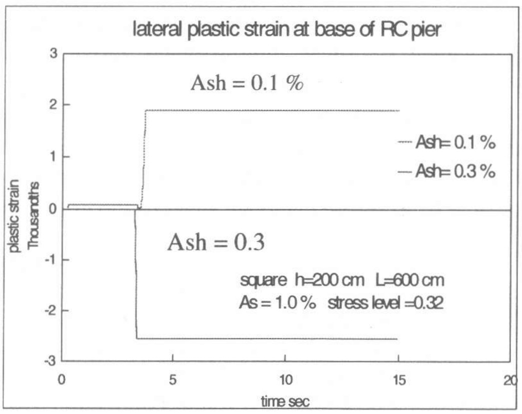

Fig. 7) effect of shear reinforcement on plastic strain at collapsed positions of RC pier.

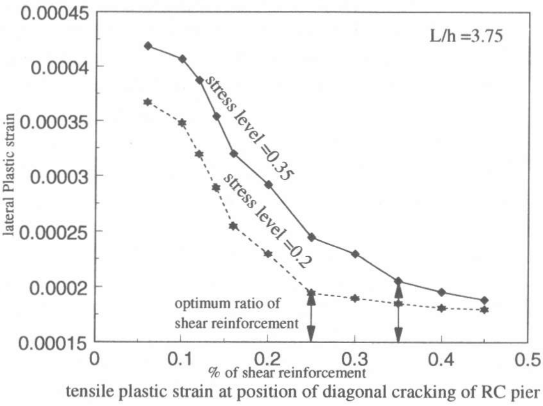

Fig. 8 determination of optimum ratios of shear reinforcement for RC bridge piers.

obtained optimum ratios of shear reinforcement for different axial stress level, pier height (L/h) and main steel ratio As %

Table 1 Optimum ratios of shear reinforcement

	L/h	stress level	Ash % at As =0.85 %	Ash % at As =1.2 %
pier 1	2.00	0.10	0.35	0.25
		0.15	0.35	0.25
		0.25	0.45	0.35
		0.35	0.45	0.45
pier 2	3.00	0.10	0.25	0.25
		0.15	0.25	0.25
		0.25	0.35	0.35
		0.35	0.45	0.45
pier 3	3.75	0.10	0.25	0.25
		0.15	0.25	0.35
		0.25	0.35	0.35
		0.35	0.45	0.45
pier 4	4.50	0.10	0.25	0.25
		0.15	0.25	0.25
		0.25	0.35	0.35
		0.35	0.35	0.35

6. CONCLUSIONS

• In this study, the role of shear reinforcement on behavior of RC piers subject to earthquake waves is focused using nonlinear three dimensional finite element approach. The main factors affecting the behavior of the piers, such as axial compressive stress level, pier size, and main reinforcement ratio, are studied. It is concluded that shear reinforcement should be high enough and range between 0.25 to 0.55 % depending on pier size, main reinforcement ratio and axial stress level. Higher percentages of shear reinforcement are recommended for piers with high axial compressive stress, small pier height and small main reinforcement ratio. Such percentage of shear reinforcement provides the piers with enough ductility to resist severe collapse during earthquake motions.

•• The optimum ratios of shear reinforcement for RC piers are obtained. Within the range of the studied cases and at the level of the given ratios of shear reinforcement, failure modes of the piers change from severe diagonal shear to flexural ones.

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