

Finite element analysis on lightweight reinforced concrete shear walls with different web reinforcement

Werasak Raongjant^{1*} Meng Jing²

¹Civil Engineering Department, Faculty of Engineering, Rajamangala University of Technology
Thanyaburi, Thailand 12110

²School of Civil Engineering, Shandong University, Shandong, PR China 266000
E-mail: werasaky@yahoo.com*

Abstract

Non-linear finite element analysis can help researchers to do more extensive investigations on the behaviours of reinforced concrete structure. A reasonable three dimensional finite element model was developed in this study to predict the seismic behaviours of lightweight reinforced concrete shear walls. Four lightweight reinforced concrete shear wall specimens with different web reinforcements, either conventionally (orthogonal grids) or with diagonal bars, were tested and simulated by this model. The comparisons of calculated results with the experimental results of the load-top displacement relationship, the shear capacity and the strain developments in steels and concrete indicate that, the finite element method presented in this study can capture the non-linear response of lightweight reinforced shear walls under earthquake load conditions. Moreover, the study on the shear transport mechanism and function of bidiagonal web reinforcements were processed, which induced that diagonal web reinforcement was effective in transferring shear force to the foundation and the shear forces carried by the compressive struts were evidently reduced due to the existing of diagonal web reinforcement.

Keywords: Shear walls, Reinforced concrete, Lightweight concrete, Nonlinear model, Shear behaviours.

1. Introduction

In the last decades, lightweight reinforced concrete shear walls have been used for reducible dead load of reinforced concrete structural members. However, further research work is needed to explore the seismic behaviour and the compute theory of this system. Due to the financial and the time reason, it is not enough that only getting the results from experiments. Finite element method supplied a new way to study shear walls by computer, which can help the researcher to analyze and complete the experimental results and have a better understanding of it.

Although there was a large amount of research in the past three decades on the finite element analysis of

reinforced concrete members, there were few studies on the behaviour of reinforced concrete members subjected to cyclic loadings. Stevens et al (1987) conducted cyclic tests on three reinforced concrete panels. The average stress-strain relationship for these panels was then used as a basis for the development of a material model for concrete. Xu (1997) proposed the model using a smeared non-orthogonal cracking approach, and Izumo et al (1989) developed the hysteresis constitutive law for reinforced concrete by combining several existing constitutive laws developed in Japan. The analytical results at the element level (a finite element model consist of one element) of these three models agreed well with the results of the panel tests.

Some researchers used the large universal software, such as MARC, ANSYS and ABAQUS, to do the study work. These software have plentiful element types and offer some default parameters, which make it easy to develop the model to simulate the cooperation work of concrete and other materials. In recent years, using ANSYS finite element software, many research works have been done successfully to simulate the seismic behavior of reinforced concrete shear walls. Monique C. Hite and Harry W. Shenton (2002) presented modeling the nonlinear behavior of wood frame shear walls. A study has been undertaken to investigate the effect of vertical load on the static and cyclic lateral load response of wood frame shear walls. John P. Judd and Fernando S. Fonseca (2002) presented nonlinear analysis of wood diaphragms and shear walls using commercial finite-element software (ANSYS and ABAQUS). In this method sheathing-to-framing connections were represented using a pair of uncoupled orthogonal nonlinear spring elements. N. Mohammad (2002) studied afterwards a numerical study on a hybrid shear wall system under cyclic load by ANSYS 5.7. However, the only work that has been done recently was the research of Lu Xinzhen and Jiang Jianjing (2003), which presented analysis for concrete structure under complex stress condition with element SOLID 65 of ANSYS. These study show that ANSYS can simulate concrete precisely.

In this study, ANSYS 8.0 was used to do the numerical study on the mechanical behavior of lightweight reinforced concrete shear walls. The

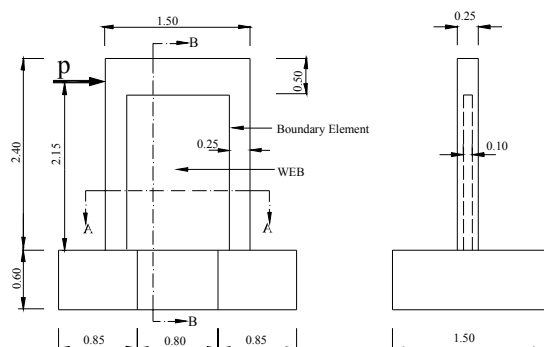
analytically predicted response of the lightweight aggregate concrete shear wall specimens were compared with the experimental results. Specifically, the analytical derived load-displacement behavior under monotonic loading was compared with the experimentally determined cyclic peak load values for successively increased displacement levels. Also the development of strain and stress in reinforcements and concrete were analyzed based on the finite element analysis results and tested results. Further studies on the shear transfer mechanisms and the function of web diagonal reinforcements of lightweight aggregate concrete shear walls were considered in this paper.

2. Test program

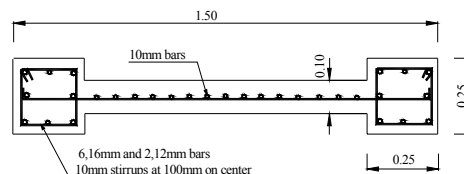
Four lightweight reinforced concrete shear wall specimens were constructed and tested to investigate the influence of diagonal web reinforcement on the hysteretic response of structural lightweight concrete shear walls. One wall contained conventional horizontal and vertical web reinforcement, one wall contained not only conventional web reinforcement but also additional diagonal web reinforcement, and other two walls contained inclined web reinforcement.

The dimensions of the specimens are shown in Fig.1. All walls had a barbell-shaped cross section with a web thickness of 100 mm and 250x250 mm boundary elements. The overall length of the cross section was 1500 mm. Vertical and diagonal reinforcement was anchored in a 600 mm thick base girder that was bolted to the laboratory floor. A 250 mm wide by 500 mm deep beam was cast on top of the wall panel, and a hydraulic actuator was attached to the specimen at mid depth of the top beam. Lateral loads were applied 2150 mm above the base of the wall.

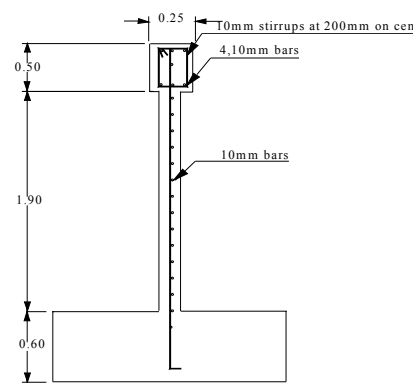
The primary experimental parameters were the amount and orientation of the web reinforcements. The longitudinal and transverse reinforcement in the boundary elements and the top beams were the same in all four specimens (shown in Fig.1 (b.c)). A single layer of web reinforcement was used in all walls. Only the web reinforcement of four specimens are shown in Fig.2.



(a) Overview of test specimens.

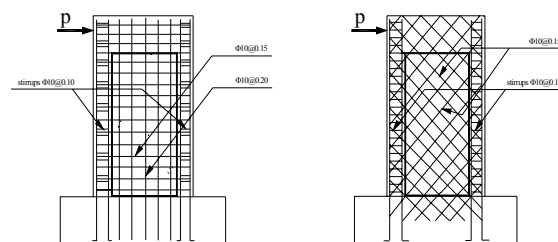


(b) Cross section A-A.



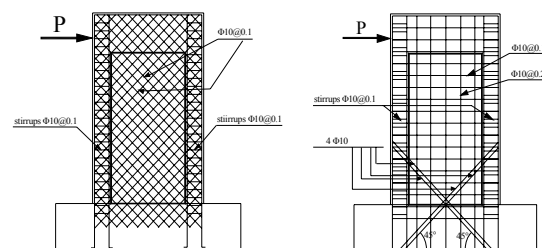
(c) Cross section B-B

Figure 1. Dimensions of test specimens.



(a) Specimen LW-1

(b) Specimen LW-2



(c) Specimen LW-3

(d) Specimen LW-4

Figure 2. Arrangement of web reinforcement in four test specimens.

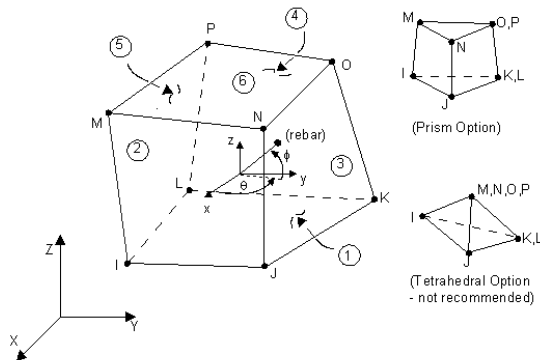
The test results showed that, walls with lightweight concrete exhibited high shear capacity, large ductility and a satisfactory energy dissipation mechanism. Walls with diagonal web reinforcement experienced less shear distortion in the lower portion than walls with conventional web reinforcement. It indicated that, diagonal web reinforcement is one approach to control structural damage reliably during earthquakes. Diagonal web reinforcement also helped to prevented deterioration of the concrete strength in the compressive struts. Due to the economic reason and the difficulties associated with placement of diagonal bars during construction, the placement of fewer inclined bars together with conventional reinforcements like specimen LW-4 provided an attractive alternative for the web reinforcement in walls. The test results were described in detail in the companion paper.

3. Finite element analysis by ANSYS

3.1 Geometrical modelling

3.1.1 Concrete

Concrete is a quasi-brittle material and has different behaviour in compression and tension. Development of a model for the behaviour of concrete is a challenging task. An eight-node solid element, SOLID 65, was used in this analysis to model the concrete. This solid element has eight nodes with three degrees of freedom at each node-translation in the nodal x, y, and z directions. The geometry and node locations for this element type are shown in Fig.3.



Figures 3. SOLID 65 geometry.

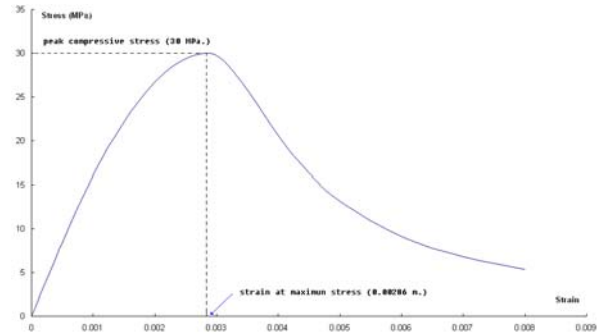
The two input strength parameters, ultimate uniaxial tensile and compressive strength, were needed to define a failure surface for the concrete. The poisson's ratio for the concrete was assumed to be 0.2. The shear transfer coefficient of open crack $\beta_t = 0.5$ and the shear transfer coefficient of closed crack $\beta_c = 0.8$. For the compressive uniaxial stress-strain relationship of concrete, the multilinear isotropic hardening model (Concrete + Miso) was used.

Numerical expression, Eq.(1), was used to construct the uniaxial compressive stress-strain curve for lightweight concrete in this study (in Fig.4).

$$f_c = (2\beta - 3) \left\{ \frac{\varepsilon_c}{\varepsilon_o} \right\}^4 + (4 - 3\beta) \left\{ \frac{\varepsilon_c}{\varepsilon_o} \right\}^3 + \beta \left\{ \frac{\varepsilon_c}{\varepsilon_o} \right\} \quad (1)$$

In which f_c is the concrete stress, ε_c is the concrete

strain and $\beta = E_{im} \frac{\varepsilon_o}{f'_c}$



Figures. 4 Compressive stress-strain curve for lightweight concrete used in ANSYS model.

In the case of lightweight concrete, the equation to calculate elastic modulus, E_{im} , proposed by Wang et al (1978) was Eq.(2).

$$E_{im} = 2.1684 f'_c{}^{0.535} \quad (2)$$

The concrete strain at peak stress, ε_o , in the case of lightweight aggregate concrete, was calculated by the equation (Eq.(3)) proposed by Almusallam and Alsayed (1984).

$$\varepsilon_o = (65.57 f'_c{}^{0.44} - 6.748) \times 10^{-5} \quad (3)$$

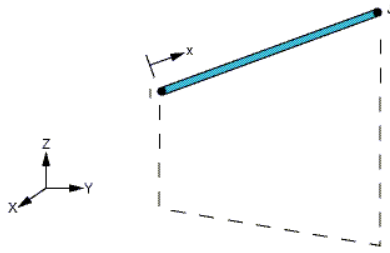
in which f'_c is the concrete compressive strength.

Once the value of f'_c is known, ε_o and E_{im} can easily be determined.

3.1.2 Reinforcement

The reinforcement bars may be incorporated in the finite element model according to either a discrete model (individual bars), or through a smeared model. In the discrete model, one dimensional elements carrying axial force are used. For the smeared model, the steel is assumed to be distributed over the concrete element with a particular orientation angle. In this study, the smeared model was used to simulate reinforcement in specimen LW-2 and LW-3 for its convenience reason, since only reinforcement ratio and steel properties of each direction need to be introduced. For specimen LW-1 and LW-4, reinforcement were modeled by using separate element called LINK 8, a 3-D spar element. The bond between concrete and reinforcement was assumed to be perfect and modelling of bond itself was not undertaken in this study.

The geometry and node locations for LINK 8 are show in Fig.5. Two nodes are required for this element. Each node has three degrees of freedom, translations in the nodal x, y and z directions.



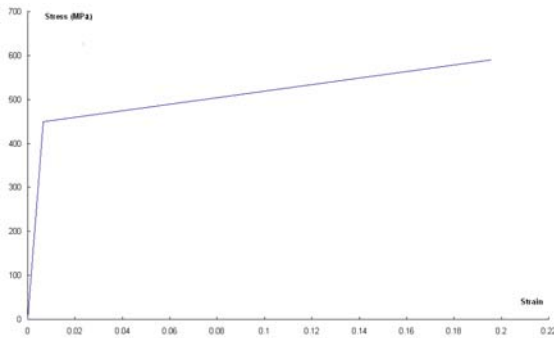
Figures 5. LINK 8 geometry.

Fig.6 shows the stress-strain relationship of reinforcement used in this study. The bilinear kinematic hardening model (BKIN) was used.

Constitutive law for steels is that

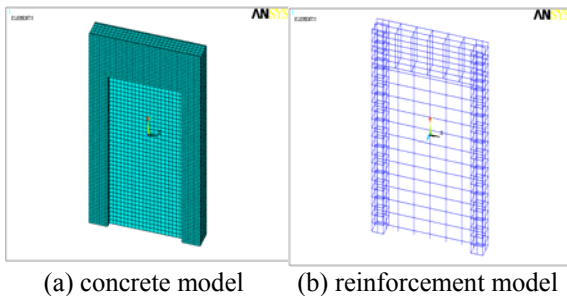
$$\begin{cases} \sigma_s = E_s \varepsilon_s & , \quad \varepsilon_s \leq \varepsilon_y \\ \sigma_s = f_y + E'_s \varepsilon_s & , \quad \varepsilon_s > \varepsilon_y \end{cases} \quad (4)$$

in which σ_s is the steel stress; ε_s is the steel strain; E_s is the elastic modulus of steel; E'_s is the tangent modulus of steel after yielding, $E'_s = 0.01E_s$; f_y and ε_y is the yielding stress and strain of steel respectively.



Figures. 6 Stress-strain curve for reinforcement in ANSYS model

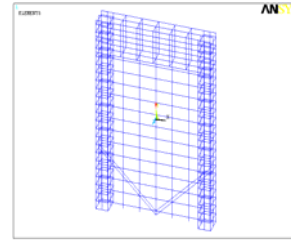
3.2 Finite mesh



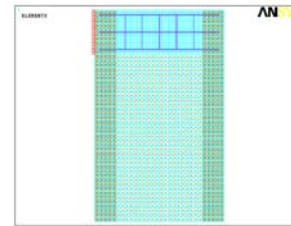
Figures. 7 Finite element model for specimen LW-1

In this study, four different three dimensional finite element models representing the four specimens with different reinforcement were generated to analytically predict the response of them under the pertinent load condition (shown in Fig.7, Fig.8 and

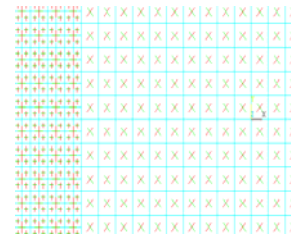
Fig.9). Concrete of the shear wall specimen was meshed with cubes element of dimension 25 mm or 50 mm and all the reinforcement were meshed with 50 mm or 100mm long link element.



Figures.8 Finite element model of reinforcement for specimen LW-4.



(a) concrete element with smeared rebar



(b) details of smeared rebar

Figures. 9 Finite element model for LW-2 and LW-3.

4. Comparison of analytical and experimental results

4.1 Force - displacement behaviours of four specimens

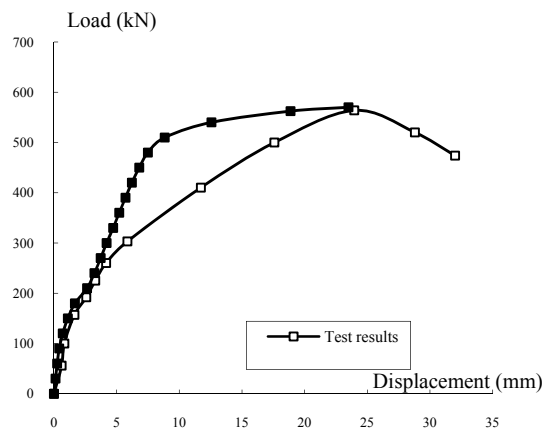
The tested and ANSYS results of top horizontal force versus top horizontal displacement curves of four specimens are shown in Fig.10. The tested results in Fig.10 present in fact the positive loading branch of the envelope of the cyclic alternating hysteretic load-displacement curves of four specimens, which cover only the first peak load values at the predetermined displacement levels. Comparing the numerical results with the experimental data, ANSYS results show similar trends to the tested results and capture well the non-linear load-displacement response of the specimens up to peak load. It indicates that the finite element analyses are capable of predicting the experimental behaviour of the specimens when these are subjected to a monotonic horizontal load.

Table 1 shows the comparison between the ANSYS calculated results and the tested results of four specimens LW-1, LW-2, LW-3 and LW-4. It is

also substantiated by the good coincidence of the peak loads that, the analytical model is indeed capable to successfully predict the shear resistance of lightweight aggregate concrete shear walls. The analytical peak load values for the four specimens are within 10% bigger than their peak tested load values.

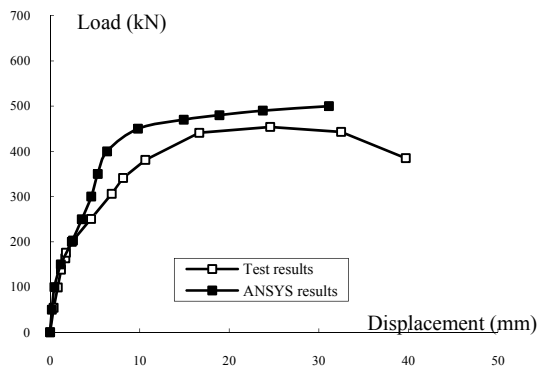
Table 1 Comparison of shear resistance for four specimens

	LW-1	LW-2	LW-3	LW-4
Test results V^{exp} (kN)	460	475	572	562
ANSYS results V^{ansys} (kN)	500	510	585	570
V^{ansys} / V^{exp}	1.087	1.074	1.023	1.014
Average value	1.0495			

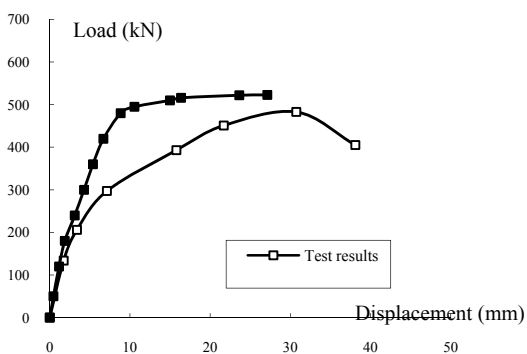


(d) LW-4

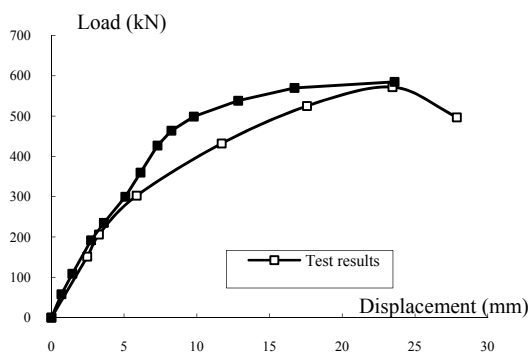
Figures. 10 Force-displacement comparison for four specimens



(a) LW-1



(b) LW-2



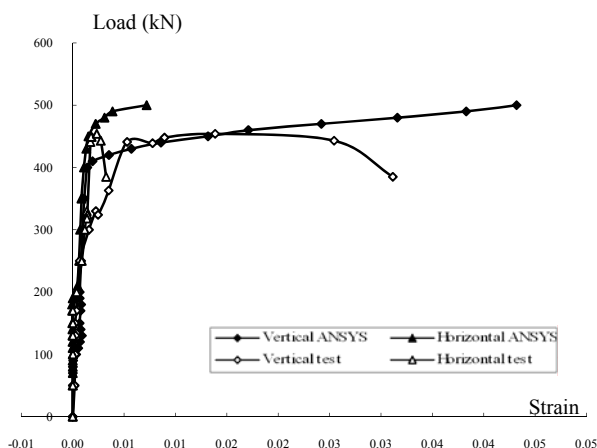
(c) LW-3

4.2 Development of the strains in steel bars

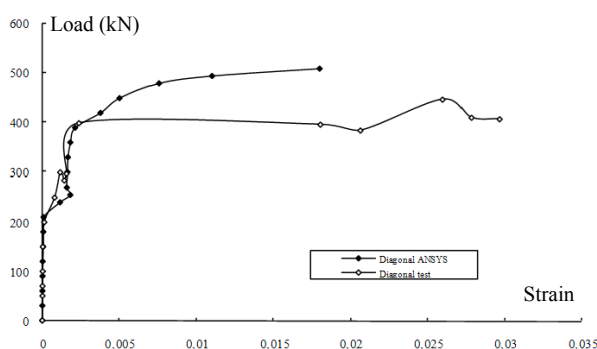
The numerical and experimental results of the strain development with increase of load in web reinforcements for specimen LW-1 are compared in Fig.11. The element chose to observe its strain lies at the same position as strain gauge S5 (vertical web steel) and S2 (horizontal web steel) of specimen LW-1 in the test. The test results in Fig.11 present in fact the positive branch of the envelope of the cyclic alternating load–strain curves of strain gauge S2 and S5, which cover only the peak load values at the predetermined displacement levels.

Similarly, the load–strain responses in web diagonal steel for specimen LW-2 from the test program are plotted with the finite element results in Fig.12. The element chose to observe its steel strain lies at the same position as strain gauge S3 of specimen LW-2 in the test. Fig.13 shows the strain development curves in web diagonal steel for specimen LW-3 from numerical and test programs. The element chose to observe its steel strain lies at the same position as strain gauge S1 of specimen LW-3 in the test. The numerical and experimental results of the strain development with increase of load in web reinforcement for specimen LW-4 are compared in Fig.14. The element chose to observe its strain lies at the same position as strain gauge S5 (vertical web steel), S2 (horizontal web steel) and S13 (tension diagonal web steel) of specimen LW-4 in the test.

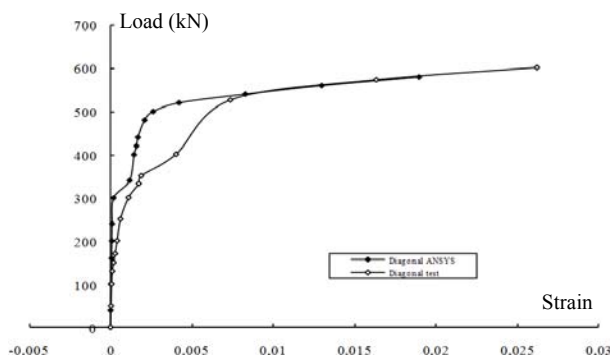
The load–strain responses for three walls are captured well by the numerical simulation. The difference between the experiment and FE results is mainly because that, the position of strain gauge in the test is not absolutely consistent with the calculated point in finite element model. The difference of smear crack and cracks in actual shear walls, the measure error of the strain gauge may also results in the differences.



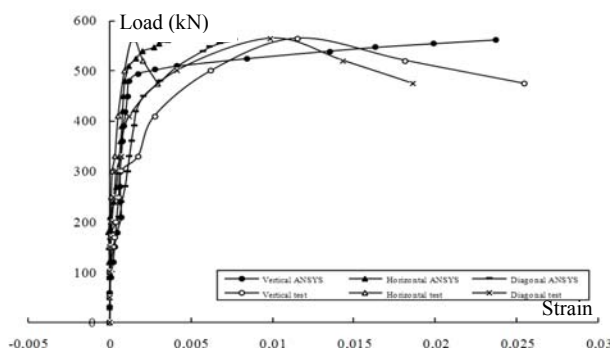
Figures. 11 Strain in steel of LW-1



Figures. 12 Strain in steel of LW-2



Figures. 13 Strain in steel of LW-3



Figures. 14 Strain in steel of LW-4

5. Conclusion

- (1) Although the proposed material models in this investigation were not capable of reproducing all observed aspects in lightweight reinforced concrete shear walls, the finite element analysis could still provide a wide-range of information that were useful for the study of the behaviour of lightweight reinforced concrete shear walls. The calculated and tested results of horizontal load versus top displacement curves of four specimens showed a good agreement. Moreover, the load-strain responses in steel for four walls were captured well by the numerical simulation. The finite element models of four lightweight aggregate concrete shear walls, constructed in ANSYS 8.0 using elements SOLID 65 and LINK 8 in this study, could capture the non-linear response of these systems under earthquake load conditions.
- (2) The dedicated element employed a smeared crack model to allow for concrete cracking with the option of modelling the reinforcement in a distributed or discrete manner. For a known compressive strength of concrete, which can be measured from concrete cubes, existing rules for the elastic modulus and concrete tensile strength were adequate for inclusion in the numerical models. It was found that for the optimum modelling strategy, controlling mesh density, defining appropriate material properties and accurately locating the internal reinforcement were very important.
- (3) The load-stress development curves of concrete and steel rebar for four specimens with different reinforcement based on the finite element model results were compared in detail. It indicated that, diagonal web reinforcement was effective in transferring shear force to the foundation and the shear forces carried by the compressive struts were evidently reduced due to the existing of diagonal web reinforcement.

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