Nonlinear Finite Element Analysis of Reinforced Concrete Beams with a Small Amount of Web Reinforcement under Shear

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Received on: 19/6/2008
Accepted on: 22 /1 /2009

Abstract

This research work presents a nonlinear finite element investigation on the behavior of reinforced concrete beams with a small amount of web reinforcement under shear. This investigation is carried out in order to get a better understanding of their behavior throughout the entire loading history.

The three- dimensional 20-node brick elements are used to model the concrete, while the reinforcing bars are modeled as axial members embedded within the concrete brick elements. The compressive behavior of concrete is simulated by an elastic-plastic work-hardening model followed by a perfectly plastic response, which terminated at the onset of crushing. In tension, a fixed smeared crack model has been used.

Keywords: Finite element method; Small amount web reinforcement; Shear.

التحليل غير الخطي بإستخدام طريقة العناصر المحددة للعتبات الخرسانية المسلحة الحاوية على كمية قليلة من اطواق الحديد التسليح والمعرضة لاحمال القص

الخلاصة

تم في هذا البحث اختبار سلوك العتبات الخرسانية المسلحة الحاوية على كمية قليلة من اطواق الحديد التسليح والمعرضة لاحمال القص باستخدام انموذج التحليل غير الخطي بطريقة العناصر المحددة. هذا الانموذج استخدم للحصول على تفهم افضل لتصرف هذه الاعضاء من خلال تاريخ التحميل الكامل تم استخدام العنصر الطابوقي ذو العشرين عقدة لتمثيل الخرسانة اما قضبان التسليح فقد مثلت كعناصر احادية البعد مطمورة في العنصر الخرساني ثلاثي الابعاد تم تمثيل تصرف الخرسانة تحت تاثير اجهادات الضغط بالانموذج المرن-اللدن ذو التقوية الانفعالية حيث يتضمن هذا الانموذج افتراض سلوكاً مرناً للخرسانة في مستهل التحميل يعقبه سلوك مرن – لدن عند حدوث التشقق في الخرسانة ،ويستمر تحمل الاجهادات بمعدل انفعال متزايد لحين وصول مرحلة اللدونة التامة، وتنتهي هذه المرحلة بحدوث تهشم في الخرسانة اما سلوك الخرسانة تحت تاثير اجهادات الشد فقد تم تبني انموذج التشقق المنتشر لتمثيله.

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1-Introduction

The amount of stirrup has a direct relation on the behavior of the reinforced concrete members of a general structure, since the structures are possible to fail in brittle manner without any warning sign if the shear stress rides over the shear carrying capacity.

Great example of shear failure is the collapse of super-structures during Great- Hanshin Earthquake, in 1995. With respect to that evident, many of viaducts structures constructed as a rigid-framed [1] were destructed.

According to the mentioned structure, the amount of stirrup was lightly used. Therefore, the following question has been asked by many researchers for such a long time that did the estimation of shear strength of those was miscalculated?

One of possible and discovered reason is the size effect of the structure members, which was introduced by Okamura [2]. With respect to this reason, the formula derived from the specimen in experiments, which are very tiny compare to the real structure, did not include some important factor. It can be illustrated that the strength of a small specimens in experiments are affected in crack propagation by the reinforcing bar, so called bond effect, which increased the fracture energy of concrete.

Nevertheless, in actual, the effect of bond from the reinforcement is very tiny since the members cross-section is so large that crack propagation is not able to confine by bond effect of reinforcement. It is used to clarify and accept this problem, size effect, by many researchers [3, 4] and the consideration in its was added as size effect term in the shear strength design formula.

2-Research Significance

The main objective of this study is to investigate the behavior of reinforced concrete beams with a small amount of web reinforcement under shear using a three-dimensional nonlinear finite element model. The 20-node isoperimetric brick elements are used to model the concrete, while the steel bars are modeled as axial members embedded within the concrete brick element, assuming perfect bond between the concrete and steel. The material nonlinearity due to cracking of concrete, crashing of concrete, yielding of reinforcement and nonlinear stress-strain response of reinforced concrete beams with a small amount of web reinforcement in compression are considered.

The behavior of reinforced concrete beams with a small amount of web reinforcement in compression is simulated by an elasto-plastic strain-hardening model followed by perfectly plastic plateau, which is terminated at the initiation of crushing. In tension, a smeared crack model with fixed orthogonal cracks has been used to simulate the behavior of concrete.

3-Finite Element Program

In this study, concrete is presented by using the 20-node quadratic brick elements shown in Fig. (1), while the reinforcing bars are modeled as 1-dimensional elements subjected to axial force only. These elements are embedded within the concrete brick elements and perfect bond is assumed to occur between the two materials.

An elasto-plastic strain-hardening model followed by perfectly plastic response simulates the behavior of concrete in compression. This response is terminated at the onset of crashing. In tension, a fixed smeared crack model has been used with a tension-stiffening model to represent the retained post-cracking tensile stresses and a shear-retention model that modifies the shear modulus of rigidity of concrete due to cracking.

In this study, a plasticity-based model is adopted for the nonlinear three-dimensional finite element analysis of reinforced concrete beams with a small amount of web reinforcement under static loads. The plasticity model in compression state of stress has the following: [5]

1. Yield Criterion
2. Hardening Rule
3. Flow Rule
4. Crushing Condition

In tension, linear elastic behavior prior to cracking is assumed. A smeared crack model with fixed orthogonal cracks is adopted to represent the fractured concrete. The model has been described in terms of the following:

1. Cracking Criterion
2. Post-Cracking Formulation
3. Shear-Retention Model.

Details of the finite element models are given in reference [5].

4-Analysis of Reinforced Concrete Beams with a Small Amount of Web Reinforcement under Shear

In this section, an investigation on the nonlinear behavior and the load carrying capacity of the reinforced concrete beams with a small amount of web reinforcement under shear is conducted using the adopted nonlinear finite element model. The aim of this section is to verify the efficiency and accuracy of the model to simulate the load-deflection response of reinforced concrete beams with a small amount of web reinforcement at the elastic, cracking and post-cracking stages of the behavior and the response at ultimate loads.

The experimental work has been considered in this study was conducted by Songkram Piyamahat et al [6].

4-1-Description of Songkram Piyamahat et al Beams

Four reinforced concrete beams are designed and used in experiment with the same dimension but varying amount of web reinforcement to be less than 0.08%. As design is, the beams have unbalancing in shear span ratio, a/d, which they approximately equal to 3 in left span and 1.5 in right span. Respect to the target of the test, the right span has to highly reinforce with D10 bars to gain its ultimate strength higher than that of left span side. Table (1) illustrates the properties of the selected beams. Fig. (2) and Table (2), show the details of reinforcement, the beams cross-section and scale down specimens layout are shown.

4-2-Finite Element Idealization and Material Properties

By taking advantage of symmetry, a segment representing half of the beam has been considered in the finite element analysis, as shown in Fig. (3). The selected segment was modeled using 20 node isoparametric brick elements. The 27-point integration rule has been generally used to carry out the numerical integration.

The external loads were initially applied in equal increments. The loading increments at stages close to the ultimate load were smaller than those used at early stages of loading. The finite element mesh, boundary and symmetry conditions used in the analysis are shown in Figs. (4). Material properties and numerical parameters of the tested beams are listed in Table (3).

4-3-Results of Analysis

In this section, the numerical results obtained for the four beams are compared with the experimental data as shown in Figs. (5) to (8). The ratio of the experimental ultimate loads to the corresponding values of the numerical ultimate load for beams B1, B2, B3 and B4 were 1.03, 1.09, 1.06, and 1.05 respectively. Generally good agreement was obtained in the pre-cracking and post-cracking stages of behavior for all tested beams. The experimental and numerical shear capacity and the ratio of the experimental shear capacity to the numerical ultimate shear capacity for the tested beams are listed in Table (4).

4-4-Parametric Study

In this section, a parametric study includes the grade of concrete, amount of longitudinal reinforcement, and shear carrying comparison among beams. The numerical study, which has been conducted in this section, is presented on two of the analyzed beams B1 and B2.

4-4-1-Influeance of grade of concrete

Figs. (9) and (10) show the effect of using higher values of compressive strength of concrete, on the load-deflection behavior of beams B1, and B2. Different values of compressive strength of concrete were used in these analyses. The Figures indicate that the increase in the magnitude of compressive strength of concrete, from the value given in the experimental work (41.7 MPa, for beam B1 and 43.5 MPa for beam B2) to 60.0 and 80.0 MPa leads to appreciable increase of the predicted post-cracking stiffness of the beams. The increase in the value of the compressive strength of concrete results in a substantial increase in the ultimate load. The shear capacity obtained from this study is listed in Table (5).

4-4-2-Effect of Amount of longitudinal Reinforcement

The influence of using different longitudinal reinforcement ratios on the load-deflection curve is investigated. In (case-1), (case-2) and (case-3) the areas of longitudinal reinforcement were 380.12, 490.85 and 615.66 mm^2 respectively. Case-1 represents the beam cross-section with the same amount of steel bars as used in the experimental tests of beams B1 and B2. Figs. (11) and (12) exhibit the effect of variation of the amount of longitudinal reinforcement on the load-deflection response of reinforced concrete beams with a small amount of web reinforcement. The increase in the amount of longitudinal reinforcement substantially affects the overall shape of the load-deflection curves and the shear carrying capacity. Table (6) shows the influence of the longitudinal reinforcement on the ultimate shear capacity.

4-4-3- Shear Carrying Comparison among Beams

Beams behaviors under shear are conducted using the adopted nonlinear finite element model were explained as aforementioned; currently, shear carrying capacity of all beams are going to be compared. Since the compressive strength in each beam is different; therefore, the comparisons have to be done by normalizing compressive strength. Fig. (13) shows the comparing result by normalizing the compressive strength of concrete, on the load-deflection behavior of beams with web reinforcement ratio equal 0.035%, 0.05%, 0.065%, and 0.08%. As observed from Fig. (13), the effect of the web reinforcement ratio on shear carrying capacity of all beams is still the same. The shear capacity obtained from this study is listed in Table (7).

5-Conclusions

1. The three-dimensional nonlinear finite element model used in the present research is able to simulate the behavior of reinforced concrete beams with a small amount of web reinforcement under shear loading. The numerical analyses carried out showed that the predicted load-deflection curves are in good agreement with the experimental results for different beams with a small amount of web reinforcement.
2. The finite element solutions show that the value of concrete compressive strength can significantly influence the post-cracking stiffness and the ultimate shear capacity. The results revealed that an increase of 10.6% and 9.1% in the ultimate shear capacity has been achieved for beams B1 and B2 respectively, when the compressive

strength of concrete is increased from 60MPa to 80MPa.

3. The analysis result of using different bottom steel bars in reinforced concrete beams with a small amount of web reinforcement under shear showed that the increase in the amount of bottom reinforcement from 380.12mm2 to 490.85mm2, leads to an increase of 24% and 23% in the ultimate shear capacity of beams B1 and B2 respectively. While the increase in the amount of the same bars from 380.12mm2 to 615.66mm2 leads to a increase of 42% and 38% in the ultimate shear capacity of beams B1 and B2 respectively.
4. For a constant compressive strength of concrete, the increase in the web reinforcement ratio, leads to a small increase in the value of ultimate shear capacity and load- deflection is stiffer.

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Table (1) Shear carrying capacity used for Songkram Piyamahat et al, beams

Specimen	Spacing of web reinforcement (mm)	Vu, (KN)
B1	D4@ 80	226.6
B2	D4@ 100	187.8
B3	D4@ 130	190.8
B4	D4@ 180	187.5

Table (2) Steel bars properties used for Songkram Piyamahat et al, beams

Steel type	Nominal dia. (mm)	Yield strength (MPa)	Ultimate strength (MPa)
D4 (SD 295)	4.0	350	457
D10 (SD345)	10.0	391	586
D22(USD 685)	22.0	718	985

Table (3) Concrete properties and additional material parameters used for Songkram Piyamahat et al, beams

Beam Designation	B1	B2	B3	*B4*
Young's Modulus, E_c (GPa)	30.27	30.99	30.35	31.93
Compressive Strength $f_c^{/}$ (MPa)	41.5	43.5	41.7	46.15
Tensile Strength, F_t (MPa)	3.74	3.88	3.74	3.94
Poisson's Ratio, ν	0.2	0.2	0.2	0.2
Uniaxial Crushing Strain	0.005	0.005	0.005	0.005

Table (4) Comparison between numerical and experimental ultimate Shear Capacity of Songkram Piyamahat et al, beams

Beam	Analytical ultimate shear capacity, V_{UA} (kN)	Experimental ultimate shear capacity, V_{UE} (kN)	V_{UE}/V_{UA}
B1	235	226.6	1.03
B2	207	187.8	1.09
B3	204	190.8	1.06
B4	198	187.8	1.05

Table (5) Effect of the grade of concrete on the analytical ultimate shear capacity of beams B1 and B2

Beam (B1) f'_c, (MPa)	Exp. ultimate shear capacity, V_{UE} (kN)	Num. ultimate shear capacity, V_{UN} (kN)	$\frac{V_{UN}}{(235)}$	Beam (B2) f'_c, (MPa)	Exp. ultimate shear capacity, V_{UE} (kN)	Num. ultimate shear capacity, V_{UN} (kN)	$\frac{V_{UN}}{(207)}$
41.7	226.6	235	1.000	43.5	187.8	207	1.000
60.0	_	253	1.08	60.0	_	240	1.16
80.0	_	280	1.19	80.0	_	262	1.26

Table (6) Effect of the longitudinal bottom steel reinforcement on t he analytical ultimate shear capacity of beams B1 and B2

	Beam B1		Beam B2	
Area of steel bars (mm^2)	Num. shear capacity, V_{UN} (kN)	$V_{UN}/(235)$	Num. shear capacity, V_{UN} (kN)	$V_{UN}/(207)$
380.12	235	1.00	207	1.00
490.87	292	1.24	254	1.23
615.75	334	1.42	286	1.38

Table (7) Effect of web reinforcement ratio on the analytical ultimate shear capacity of beams by normalizing compressive strength

	Beams	Web reinforcement ratio Pw	Num. ultimate shear capacity, V_{UN} (kN)	V_{UN}/(206)
Normalizing compressive strength f 'c = 30MPa	B1	0.08%	206	1.00
	B2	0.065%	201	0.98
	B3	0.05%	198	0.96
	B4	0.035%	195	0.95

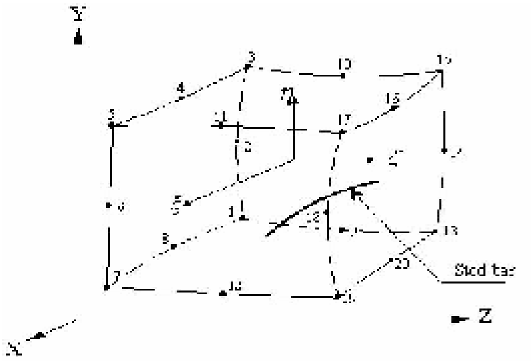

Fig.(1) 20-node brick element

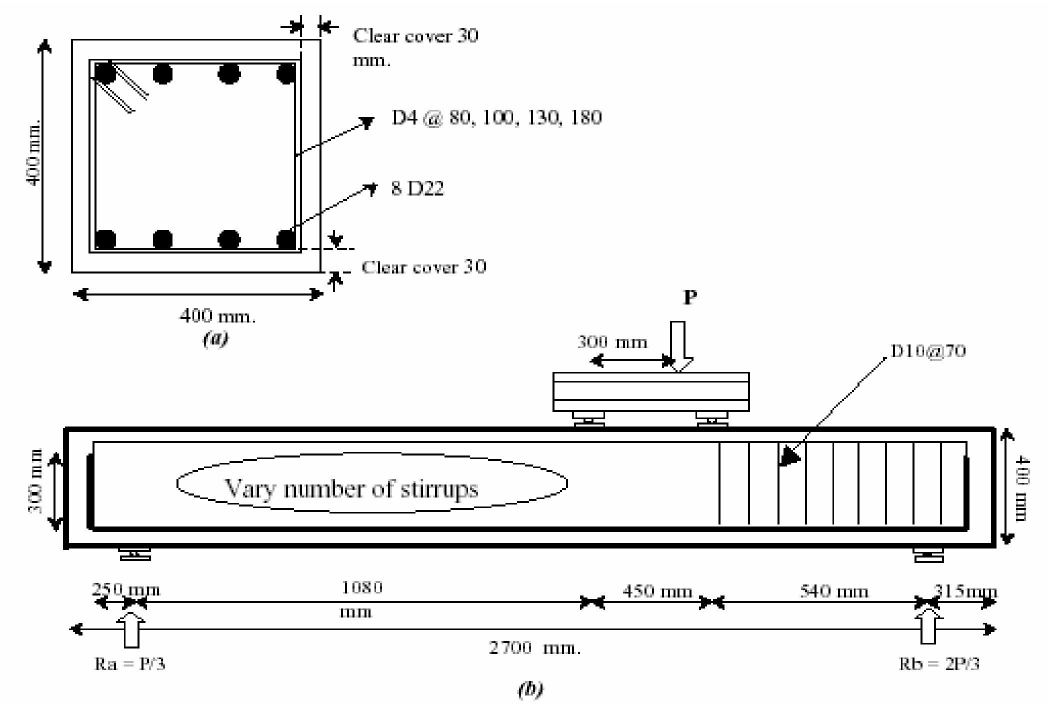

Fig. (2) Dimensions and reinforcement details of Songkram Piyamahat et al, beams

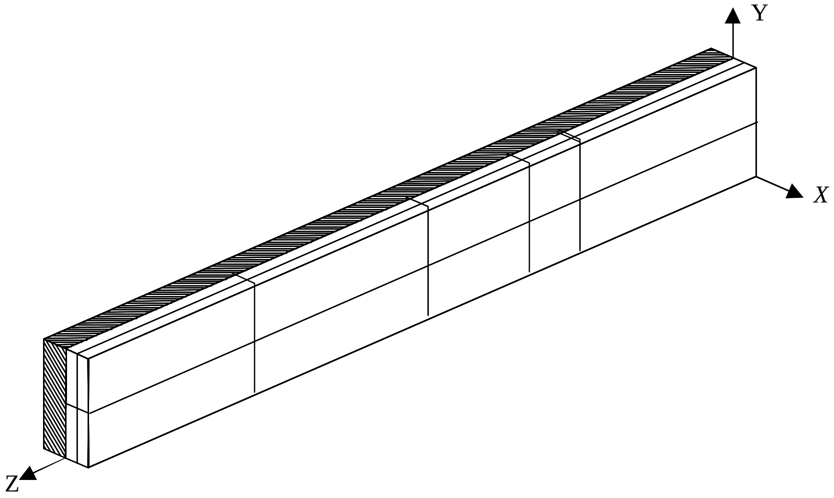

Fig. (3) Finite element mesh and symmetry conditions used for Songkram Piyamahat et al, beams

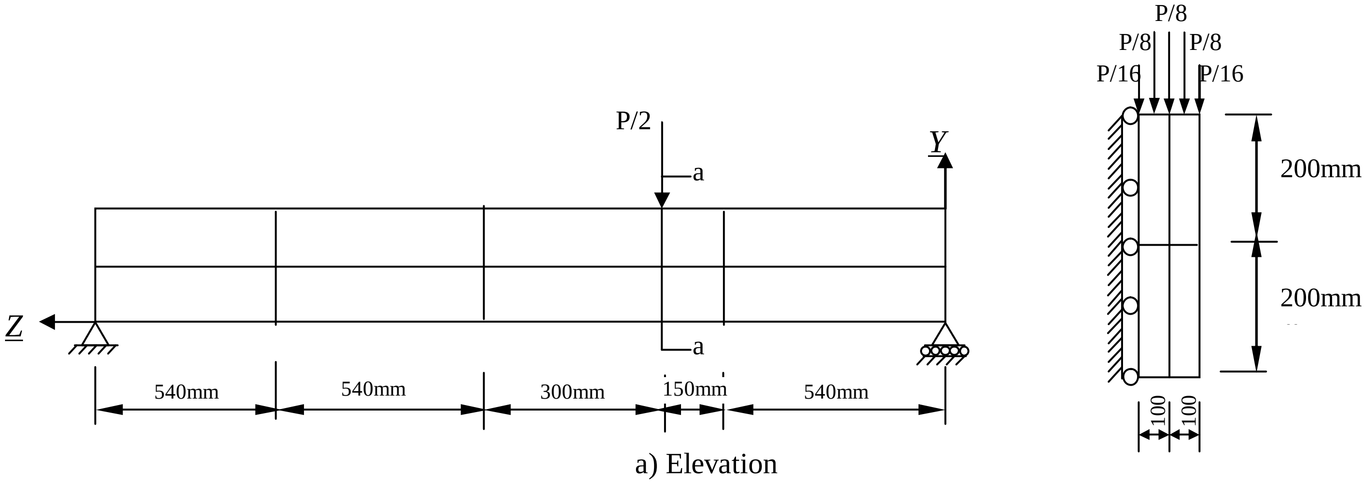

Fig. (4) Finite element mesh and boundary conditions used for Songkram Piyamahat et al, beams

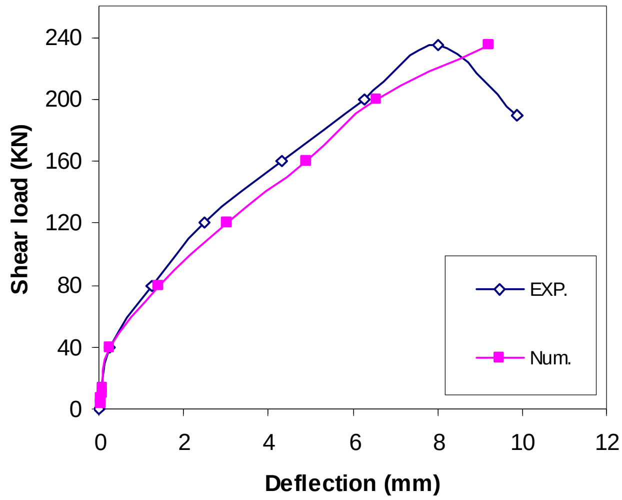

Fig. (5) Experimental and numerical response for beam B1

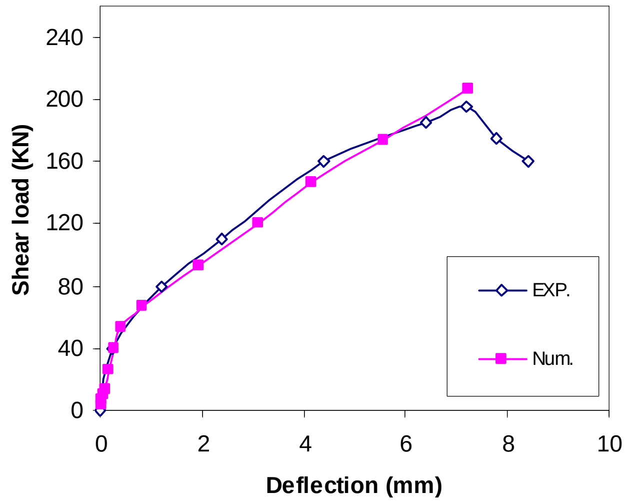

Fig. (6) Experimental and numerical response for beam B2

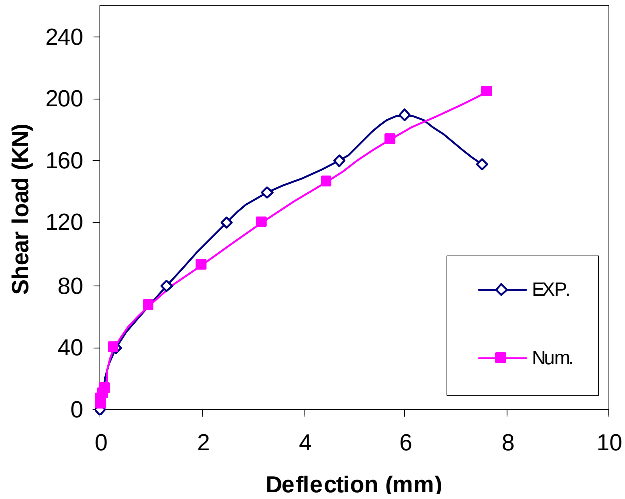

Fig. (7) Experimental and numerical response for beam B3

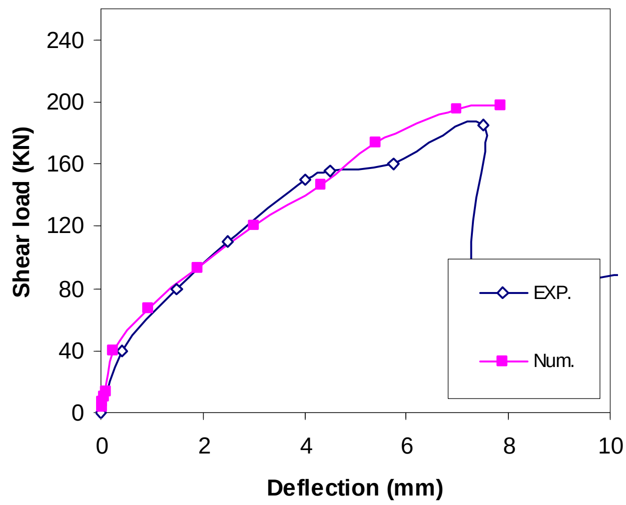

Fig. (8) Experimental and numerical response for beam B4

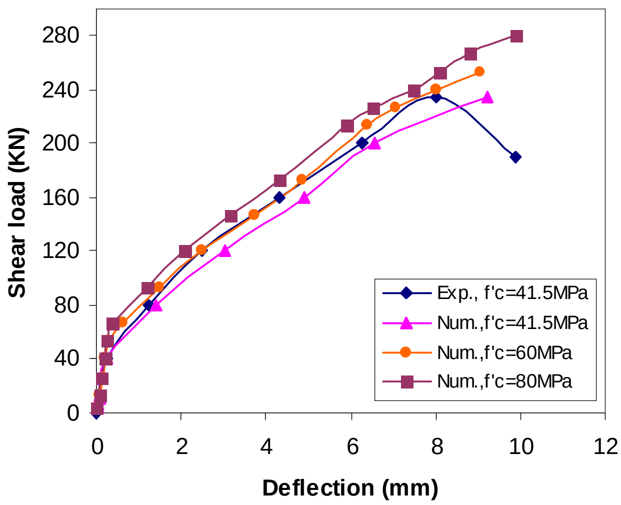

Fig. (9) Effect of the concrete compressive strength on the load-deflection behavior of beam B1

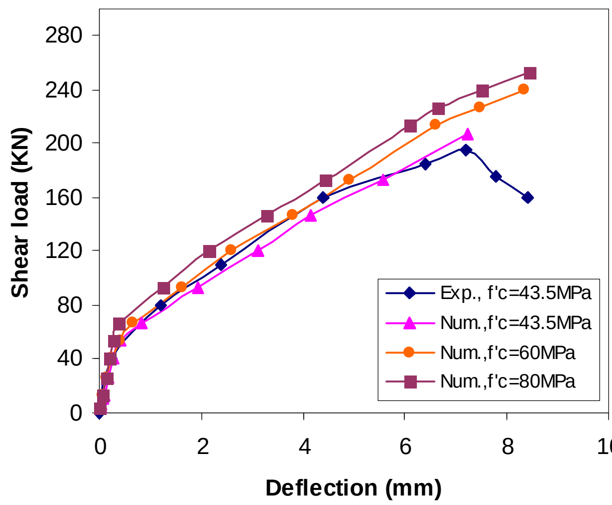

Fig. (10) Effect of the concrete compressive strength on the load-deflection behavior of beam B2

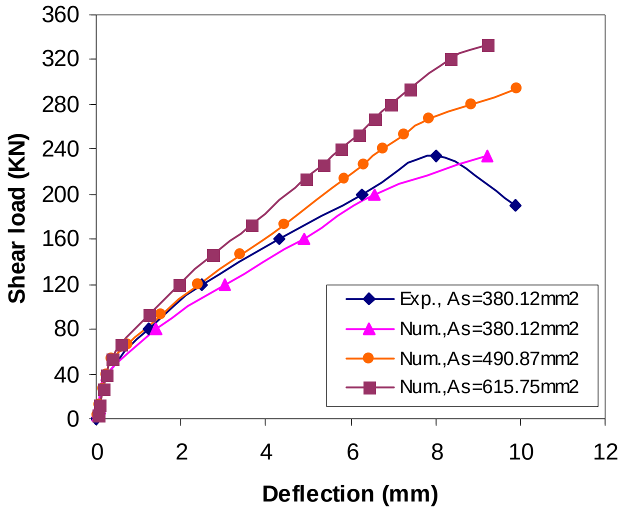

Fig. (11) Effect of the longitudinal tensile reinforcement on the load-deflection behavior of beam B1

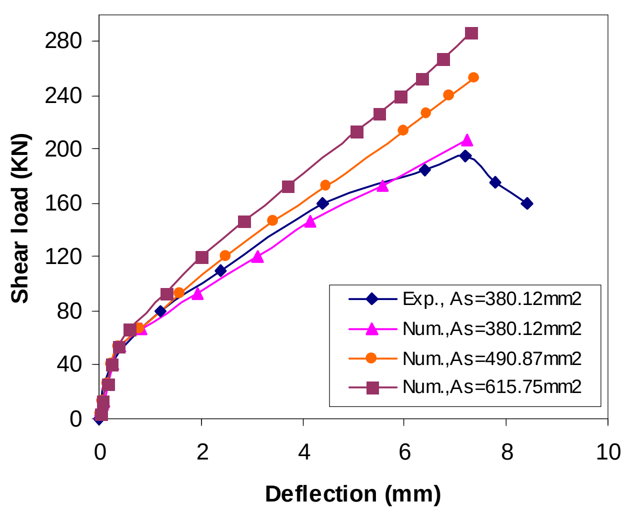

Fig. (12) Effect of the longitudinal tensile reinforcement on the load-deflection behavior of beam B2

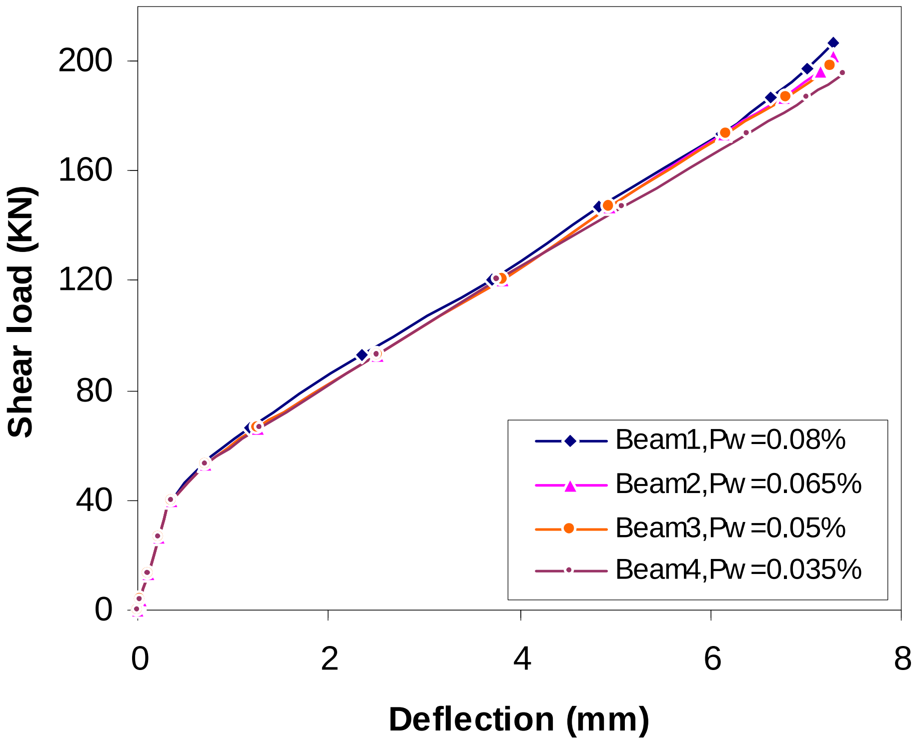

Fig. (13) Effect of web reinforcement ratio on the analytical ultimate shear capacity of beams by normalizing compressive strength