Finite element modeling of high-strength fiber reinforced beam-column joints

Jamal A. Farhan

Zaid M. Kani

Lecturer, Civil Engineering Dept. College of Engineering, University of Anbar Lecturer, Dams and water resources Engineering Dept. College of Engineering, University of Anbar

ABSTRACT: The frames in reinforced concrete structures are referred as "RIGID FRAMES". However, researches indicate that the Beam-Column Joint (BCJ) is definitely not rigid. In addition, extensive research shows that failure may occur at the joint instead of at the beam or the column. Joint failure is known to be a catastrophic type which is difficult to repair.

This study was carried out to investigate the behaviour and strength of highstrength fibre reinforced Beam-Column Joints by developing a numerical model based on finite element method using computer program ANSYS (Version 11.0). The variables are: type and volume fraction of fibers.

The theoretical results obtained from ANSYS program are in good agreement with previous experimental results so that the analytical model can be used instead of experimental model which may be expensive and time consuming.

Keywords: High Strength Concrete (HSC), Fiber Reinforced Concrete, Finite Elements, Beam-Column Joints (BCJ), ANSYS

INTRODUCTION

In building analysis and design, in general, the structures that contain slabs, beams and columns are referred as "Rigid Frames". However, research indicates that, both in reinforced concrete and structural steel frames, the beam-column joint is definitely not rigid; it is subjected to deformation under all types and stages of loading. In addition, extensive research shows that failure may occur at the joint instead of at the column or the beam. Thus, another way of looking at a joint is to consider it as a member of the structure, as is the case for slabs, beams, columns and etc (Kani 1997).

In general the adequate performance of beam-column joints depends primarily on providing the principal requirements for shear strength, confinement and anchorage of reinforcement passing through or terminating in the joint.

Some researches studied the effect of using fiber reinforcement on the beamcolumn joints and it has been shown from these researches that:

- a. The congestion of steel reinforcement in the joint region make the construction more difficult, steel fibers in reinforced concrete increases the joint hoop spacing which makes the construction easier (Gefken 1989 and Jindal 1984).
- b. A fiber reinforced beam-column joint provides better confinement of concrete (Gefken 1989 and Craig 1984)

- c. The shear capacity of fiber reinforced beam-column joints is more than that of conventional one (Gefken 1989 and Jindal 1984).
- d. The anchorage bond strength of deformed bars in fiber reinforced beam-column joints is higher than in the conventional joints (Henager 1997).
- e. The number of cracks is greater but their size is smaller (Craig 1984).

With the production of High Strength Concrete, enhanced material properties such as increased compressive and tensile strength and elastic modulus can be achieved.

This study was carried out to investigate the behaviour and strength of highstrength fiber reinforced beam-column joints by developing analytical model based on finite element method and using computer program ANSYS (Release 11.0, 2007). The variables considered are: Type and volume fraction of fibers.

The comparison between the theoretical results obtained from the suggested model and the experimental results from previous research (Kani 1997) shows a good agreement.

TESTING PROGRAM

The specimens are classified into two groups. Group.1 specimens contain hooked fibers while group.2 specimens contain straight fibers. Each group consists of three specimens having a volume fraction of fibres equals to 0.5%, 1% and 1.5%. In addition to these two groups a control specimen having 0% of fibers is tested as a reference case, thus the total number of specimens is seven. Table.1 shows the designation and properties for specimens.

All the seven beam-column joints have identical beam and column sizes. Figure.1 shows the details of the specimens, these dimensions were used previously by several investigators (Taylor 1974, Sarsam 1983 and Al-Jubbori 1986). The beams were 300mm depth by 150 mm width and columns were 200 mm depth by 150 mm width.

All columns were reinforced with four 16 mm longitudinal bars and 8 mm closed ties at 85 mm centre to centre spacing. All beams were reinforced with three 18 mm bars on tension side and 12 mm bars on compression side. This resulted in an under-reinforced beam with tension steel percentage slightly under 1.9%. Beam stirrups were 8 mm closed ones spaced at 130 mm centre to centre.

Ordinary Portland cement from Kubaysa factory was used. This cement conforms to Iraqi standards (Iraqi standards 1985). It has already been found that this cement was the most suitable for high strength concrete (Abdullah 1985).

Fine aggregate passing through 4.75mm sieve conforming to ASTM C33 specifications (ASTM 1989) was used; the fineness modulus equals 2.5 and a specific gravity of 2.6.

Natural coarse aggregate was used. Many references have shown that the smaller size aggregates produce higher strength values. Therefore the maximum size was chosen to be 9.5 mm. The grading of these aggregates conforms to ASTM C33 specifications (ASTM 1989). The specific gravity of the aggregate was 2.7.

For high strength concrete production the water content of mix is reduced, and the associated reduction in workability is compensated for by using super plasticizers which are chemical admixtures. The optimum dosage for this admixture is found to be 5% of weight of cement and the reduction of water for this dosage was 27.7%.

Three samples of reinforcing steel bars for each size of bars (8,12,16, and 18)mm were tested. Further tests on separate samples were made using the Instron testing machine. Results were automatically recorded by a plotter, which was

attached to the testing machine. The purpose of these tests was to determine the stress strain relationship of the bars.

The cylindrical compressive strength (f'_c) , the modulus of rupture (f_r) , poisons ratio (v) and modulus of elasticity (E_c) for the concrete of the seven specimens are included in Table.2

EXPERIMENTAL PROGRAM

The testing rig dimensions were (3x4) m with a depth of 1.1m. The testing rig consisted of a reinforced concrete mass with a special reinforcing bars used for fixing the large steel I-sections as reaction points for bracing the specimens and applying the loads. It was insured that the testing rig was stiff enough to resist all possible loadings.

The specimens were tested using two hand operating jacks; the first is used to apply the column axial load (N_u) , while the second is used to apply the beam load (V). Ball and socket type hinges, designed and constructed especially for allowing rotation in the plane of the frame only, were used to brace the columns from the two sides and the bottom. However for the loading points under the two jacks, roller type hinges designed and constructed especially for allowing movement in the direction perpendicular to the applied load only, were used to eliminate fixity. All these details are illustrated in Figure.2

ANALYTICAL MODELLING

The building of the analytical model consists of:

Element Type

The beam-column joint was modelled in ANSYS (Release 11.0, 2007) with Solid 65, Solid 45 and Link 8 elements. The Solid 65 element was used to model the concrete and Solid 45 was used to model steel plates at supports and under testing loads. These elements have eight nodes with three degrees of freedom at each node which is the translations in x, y and z directions. The Link8 element was used to model reinforcement. This three dimensional bar element has two nodes with three degrees of freedom at each node which is translations in x, y and z directions.

Sectional properties (Real Constants)

The real constants considered for Solid 65 were volume ratio and angle of orientation of reinforcement. Since there was no smeared reinforcement, the real constants (volume ratio and orientation angles) were set to zero. No real constant sets exist for Solid 45 element. The real constant that considered for Link8 elements is sectional area.

Material Properties

Parameters needed to define the material models can be found in Table.3. As seen in this table, there are multiple parts of the material model for each element. Material model number 1 refers to Link8 element which is used to model reinforcing bars. Figure.3 is used to define the bilinear stress-strain relationship of steel bars which consists of two branches: A first branch starts from the origin with a slope equal to E_{s} up to f_{y} . A second branch is horizontal or, for the computer solution convergence is assumed to have a very small slope such as $10^{-4}E_{s}$ and this last case is limited to the strain 0.01 according to EC4. The material properties of 12mm bar diameter are used for example.

Material model number 2 refers to solid65 element for specimen No.1 which is used to model concrete. The solid65 element requires linear isotropic and multilinear isotropic material properties to properly model concrete. **EX** is the modulus of elasticity of concrete (E_c), and **PRXY** is the Poisson ratio (v).For the normal weight concrete based on a dry unit weight (2200-2500 kg/m³); E_c can be permitted to be taken as (ACI 318):

$$E_c = 4700\sqrt{f_c'} \tag{1}$$

According to Bangash (Bangash 1989), the value of poisons ratio can be taken equal to (0.2). In this study the values of the modulus of elasticity and poisons ratio are determined from test and used in Table.3. According to Desayi and Krishnan (Desayi 1964). The compressive unixial stress-strain relationship for concrete model is obtained using equations (2), (3), and (4).

$$f = \frac{E_c \varepsilon}{1 + \left(\frac{\varepsilon}{\varepsilon_o}\right)^2} \quad ---(2) \qquad \varepsilon_o = \frac{2f'_c}{E_c} \quad ---(3) \qquad E_c = \frac{f}{\varepsilon} \quad ---(4)$$

Where:

f = stress at any strain ε , N/mm². $\varepsilon = \text{strain}$ at stress f. $\varepsilon_o = \text{strain}$ at the ultimate compressive strength f'_c . $E_c =$ Initial modulus of elasticity for concrete (equation 1)

The multi-linear isotropic stress-strain implemented requires the first point of the curve to be defined by the user. It must satisfy Hooks law defined by equation (4). The multi-linear curve is used to help with convergence of the nonlinear solution algorithm. In this study the concrete stress-strain relationship is determined from test and used in Table.3

Concrete material model in ANSYS (Release 11.0, 2007) requires that different constants be defined. These 9 constants are:

- 1. Shear transfer coefficients for an open crack;
- 2. Shear transfer coefficients for a closed crack;
- 3. Unixial tensile cracking stress;
- 4. Unixial crushing stress (positive);
- 5. Biaxial crushing stress (positive)
- 6. Ambient hydrostatic stress state for use with constants 7 and 8;
- 7. Biaxial crushing stress (positive) under the ambient hydrostatic stress state (constant 6);
- 8. Unixial crushing stress (positive) under the ambient hydrostatic stress state (constant 6);
- 9. Stiffness multiplier for cracked tensile condition

Typical shear transfer coefficients represent conditions of the crack face, It is value ranges from 0.0 to 1.0, with 0.0 representing a smooth crack (complete loss of shear transfer) and 1.0 representing a rough crack (no loss of shear transfer). The shear transfer coefficients for opened and closed cracks are determined using the work of Kachlakev, et al. (Kachlakev 2001) as a basis. The presence of

different ratios of steel fibers in concrete mixture affects the concrete mechanical properties significantly, which in turn affects the crack face conditions, thus a number of preliminary analyses for each specimen were attempted in this study with various values for the shear transfer coefficient to choose the appropriate value which satisfies the solution convergence.

The unixial cracking stress is based upon the modulus of rapture. This value can be determined using the equation of ACI code (ACI code 2008):

$$f_r = 0.62\sqrt{f_c'} \tag{5}$$

In this study the cracking stress is determined from test and used in Table.3. The unixial crushing stress in this model is based on the unixial unconfined compressive strength (f'_c) . In this study a value of (-1) is given to the crushing coefficient to turn off the crushing capability of the concrete element and prevent local failure. The other five coefficients are given the value 0.0.

Material model number 3 refers to solid $\overline{45}$ element which is used to model steel plates at supports and under testing loads. It requires linear isotropic properties only.

Modeling

The beam-column joint is modeled by two solid models. The block model is used to model concrete and steel plates while lines are used to model reinforcement. After the solid model is constructed, it will be meshed to form the finite element model. Figure 4, 5 and 6 shows the solid model of the beam-column joint, reinforcement and the finite element model after meshing respectively.

The loads are applied on the columns and beams through the steel plates, the axial load applied on the center of the column, while the transverse (shear) force is applied at (0.2m) from the beam end. For nonlinear solution, the shear force is divided in to small parts (time stepping).

RESULTS

The results are:

Failure Load

All specimens failed in the joint. Table.4 shows the analytical and experimental failure load and the ratio of analytical to experimental result. Figure.7 shows the cracked specimen after failure. Figure.8 shows the effect of steel fibers type and volume fraction on the capacity of the beam column joint.

Moment rigid body rotation $(M - \Phi_r)$ relationship

Because the beam and columns are connected together at the joint area, the rigid body rotation of the joint may be used as an indicator to the overall behaviour of any joint. The rotation (Φ_r) was calculated using the following equation:

$\Phi_r = tan^{-}(\Delta_{r1} - \Delta_{r2}) / h_b$

Where:

 Δ_{rI} = The average deflection of dial gauges No.3 and No.4 Fiure.9

 Δ_{r2} = The average deflection of dial gauges No.5 and No.6 Fiure.9

(6)

h_b = Beam width

The experimental and analytical values and the ratio of analytical to experimental results are included in Table.4. Figure.10 shows the effect of steel fibres and volume fraction on the rigid body joint rotation.

CONCLUSIONS

Based on the results obtained in this study, the following can be concluded:

- 1- The results predicted by the analytical model were in good agreement with the experimental data. The maximum difference in predicting the failure load is 10%. While the maximum difference in predicting the rigid body rotation is 12%.
- 2- Because the beams and columns are connected together at the joint area, the $(M-\Phi_r)$ relationship of the joint may be used as indicator to the behaviour of the joint. Test results indicate that addition of fibers into the joint region improves the overall behaviour of the specimen from this point of view.
- 3- In this work it is shown that beam column joints is definitely not rigid as it undergoes deformation at all stages of loading as indicated by $(M-\Phi_r)$ relationship. Thus, "rigid frame" design of reinforced concrete frames should take into account the behaviour of joint.
- 4- Only 0.5% and 1% volume fraction of straight and hooked steel fibers succeeded in improving the strength of beam-column joints effectively. While 1.5% volume fraction failed to increase the failure load with respect to the ratio 1%.
- 5- Both straight and hooked steel fibers can be used in construction of beamcolumn joints. The second type was more successful in improving the general behaviour of such specimens.

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TABLES

Table 1: Designation andproperties of specimens

SP	Type; V _f %		
1	0.0		
2	H 0.5		
3	H 1.0		
4	H 1.5		
5	S 0.5		
6	S 1.0		
7	S 1.5		

H&S refers to hooked and straight fibers, respectively

 Table 2: Test results of material samples

SP	Type;	f_c'	f_r	V	E _c	
	V_f %	MPa	MPa		(kN/mm^2)	
1	0.0	60.40	7.500	0.138	34.09	
2	H 0.5	64.00	9.420	0.185	33.71	
3	H 1.0	67.50	11.370	0.240	33.33	
4	H 1.5	71.00	13.250	0.282	33.85	
5	S 0.5	61.55	8.120	0.185	34.80	
6	S 1.0	62.66	8.730	0.212	34.95	
7	S 1.5	63.90	9.340	0.265	35.16	

H&S refers to hooked and straight fibers, respectively

Material Model Number	Element type	Material Properties						
	Link8	Bilinear IsotropYield stress440N Tangent20.3N			oic			
1					Yield stress		440N	/IPa
					Tangent		20.3MPa	
		Line	Linear Isotropic			ılus	,	
	SOLID65	PRX PRX	EX 20355000Pa PRXY Linear Isotrop PRXY 0. PRXY 0. Multilinear			pic		
				Str	ain	Stress		
			Point1	0.00	005	17.5MPa		
2			Point2	0.0	0.001		34.5MPa	
2			Point3	0.00)15	48.5MPa		
			Point4	0.0	02	60.4MPa		
			Point5	0.0	03	60.4MPa		
					0.15			
			ShrC	F-OP		0.15		
			JIICF-CL UnTonsSt		0.0 7 5MPa			
			UnCompSt		1.51VIF a			
			UIICO	mpst		-1]
_					Linea	r Isot	ropic	
3	SOLID45			EX 200000M		IPa		
				PR	XY		0.3	

 Table 3: Material models for the elements

Table 4: Test results of beam-column joint

SP	Type;	N _u	Ultimate Load (kN)		Analytical	Ø _r ×10	³ rad	Analytical
	V _f %0	KIN	Experi- mental	Ana- lytical	Experimental	Experi- mental	Ana- lytical	Experimental
1	0.0	100	45.2	48	1.06	5.5	6.1	1.11
2	H 0.5	100	62.3	66	1.06	6.25	6.5	1.04
3	H 1.0	100	77.5	82	1.06	7.20	7.65	1.06
4	H 1.5	100	65.0	72	1.10	5.80	6.4	1.10
5	S 0.5	100	55.9	58	1.04	6.00	6.7	1.12
6	S 1.0	100	61.6	66	1.07	6.6	7.4	1.12
7	S 1.5	100	50.5	48	0.95	5.30	5.1	0.96







Figure3: Bilinear stress-strain relationship of steel bars for computer calculations (CEN 1973)

Figure 4: Solid model of beam-column joint



Figure 5: Solid model of beam-column reinforcement

Figure 6: Finite element model of beam-column joint



Figure 7: Cracked specimen after failure



Figure 8: The effect of type and volume fraction of steel fibers on the capacity of the beam- column joint.



Figure 9: Measurement instrumentation on beam-column ioint



Figure10: The effect of type and volume fraction of steel fibers on the rigid body joint rotation.