- *Technical Paper* –

2D NUMERICAL SIMULATION OF CONCRETE COVER SEPARATION OF REINFORCED CONCRETE BEAM STRENGTHENED EXTERNALLY WITH FRP BY USING RIGID BODY SPRING MODEL

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ABSTRACT

This paper presents 2D simulation of concrete cover separation, a popular premature failure mode of FRP strengthened RC beams, by using Rigid Body Spring Model (RBSM). To simulate this complex failure mechanism, special consideration of the interfacial behavior is taken into account by applying constitutive laws for radial stress caused by tension steel and shear bond stress at the interface between steel/concrete as well as FRP/concrete. The reliability of the approach is then validated by comparing results from the analysis with those of experiments collected from other researches.
Keywords: Numerical simulation; FRP; RC beams; concrete cover separation; RBSM.

1. INTRODUCTION

In recent decades, the significant increase in the number of old and deteriorated reinforced concrete (RC) structures year by year has resulted in the need of retrofitting and rehabilitating. One of the earliest methods that has been utilized is steel plate external bonding, which was applied popularly in many countries and was studied by many researchers [1], [2]. However, this method showed some disadvantages such as steel is easy to corrode by chemicals and the bond at the interface between steel plate/concrete will be lost or difficulties in transporting and handling or installation, therefore, a new material that is superior is necessary. Recent years, using fiber reinforced polymer (FRP) as external bonding to strengthen RC structures has demonstrated extreme efficiency. It is getting as a substitute of strengthening with conventional materials such as steel plate and concrete, due to the superior characteristics of FRP, such as: high strength, high stiffness-to-weight ratio, high corrosion resistance, good fatigue strength, potential for decreasing the installation costs due to lower weight in comparison to steel, and ease of application in the site. Bonding between FRP and concrete is very important to ensure composite action between concrete and FRP. Loss of which would cause undesirable premature failure prior to the theoretical or predicted ultimate load. The RC beams strengthened externally with FRP plates reach the ultimate state with the following failure modes corresponding to the reinforcing volume and length of the FRP plate such as: 1) FRP rupture; 2) concrete compression failure; 3) shear failure; 4) intermediate crack induced delamination; and 5) concrete cover separation failure from the plate-end along the main rebar [3]. Among those five major failure modes, the first three modes can be predicted relatively exactly by applying conventional beam theory with some modifications that take into account the effect of FRP, but the latter two modes are much more complicated especially concrete cover separation failure mode. In this study, a new numerical simulation approach for concrete cover separation is presented by using the rigid body spring model (RBSM).

2. EXPERIMENTAL OVERVIEW

Many experiments and numerical works were conducted on beams strengthened with FRP sheets and plates ([4]-[9]). In this research, concrete cover separation failure mode will be simulated by a 2D RBSM program developed by the authors. Furthermore, the interfacial behavior such as: radial stress around tension steel, shear bond stress at the interface between FRP and concrete as well as bond deterioration at crack positions will also be carefully considered. In addition, modified Newton-Raphson method will be applied for nonlinear solving procedure. To validate the program, two series of FRP strengthened beams subjected to four points loading were simulated, series 1 is from Garden et al. 1997 [6] and series 2 is from Nguyen et al. 2001 [7]. The dimensions and material properties of the tested beams are given in Table 1 and Table 2 respectively. All of these FRP strengthened beams were simply supported beams with rollers at supports, which will be simulated in the program by releasing the displacement in horizontal direction and fixing displacement in vertical direction, and designed to fail in flexure and concrete cover separation.

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Table 1 Geometry of tested beams

Ref.	Specimen	b(mm)	h(mm)	h_o(mm)	a(mm)	a_v(mm)	L(mm)	f_c(MPa)	E_c(GPa)
[6]	$1B_u$	100	100	80	20	300	900	47.3	32.5
	$2B_u$	100	100	80	20	340	900	47.3	32.5
[7]	A950	120	150	125	190	440	1330	25.7	24
	A1100	120	150	125	115	440	1330	25.7	24

Note: b is width of beam; h is height of beam; h_o is effective depth of beam; a is distance from support to plate end; a_v is shear span of beam; L is span of beam; f_c is compressive strength of concrete; E_c is elastic modulus of concrete; *Ref.* is reference.

Table 2 Material properties of tested beams

Ref.	Specimen	FRP				Tensile steel			Compressive steel			Stirrup		
		E_f GMa	f_f MPa	t_f mm	b_f mm	E_s GMa	f_y MPa	(n- φ)	E_s GMa	f_y MPa	(n- φ)	E_s GMa	f_y MPa	(φ-s)
[6]	$1B_u$	111	1273	0.7	65	215	350	3-6	215	350	2-6	215	350	3-51
	$2B_u$	111	1273	0.7	65	215	350	3-6	215	350	2-6	215	350	3-51
[7]	A950	181	3140	1.2	80	200	384	3-10	200	400	2-6	200	400	6-50
	A1100	181	3140	1.2	80	200	384	3-10	200	400	2-6	200	400	6-50

Note: E_f is elastic modulus of FRP; f_f is tensile strength of FRP; t_f is thickness of FRP; b_f is width of FRP; E_s is elastic modulus of steel; f_y is yield stress of steel; *n- φ* is number of steel bars-diameter (mm); *φ-s* is diameter (mm)-distance between two stirrup (mm).

3. RIGID BODY SPRING MODEL (RBSM)

The rigid-body-spring model (RBSM) which was first developed by Kawai [10], [11] is one of the discrete approaches. RBSM is useful to simulate the discrete behavior of materials like concrete fracture. RBSM had been used to analyze the concrete and concrete structures by many researchers ([12] - [14]). The rigid body spring model RBSM represents the continuum material as an assemblage of rigid particles elements interconnected by springs. The response of the spring model provides comprehension about the interaction between particles instead of the internal behavior of each particle based on the continuum mechanics. The model is therefore suitable for problems where material discontinuities are dominant. The fracture in composite materials like concrete may be modeled as discretization of a continuum using the RBSM, since such brittle materials behave as a discontinuum when fracture occurs and progresses. Since the cracks initiate and propagate along the boundary face, the mesh procedure may affect the fracture directions. Therefore, to avoid or at least decrease the effect of mesh on the fracture directions, random geometry will be introduced by using Voronoi diagram as shown in Fig. 1. Voronoi diagram is a group of Voronoi cells. Each cell represents a concrete element. For the Voronoi meshing, geometric computational software developed by Sugihara 1998 [15] is applied. In RBSM, concrete is modeled as an assemblage of rigid particles interconnected along their boundaries through flexible interface. The interface may be viewed as springs whose initial properties can be set to approximate the overall elastic properties of the continuum. Each element has two transitional and one rotational degree of freedom at the center of gravity. Normal and shear springs are placed at the boundary of the elements (Fig. 1b).

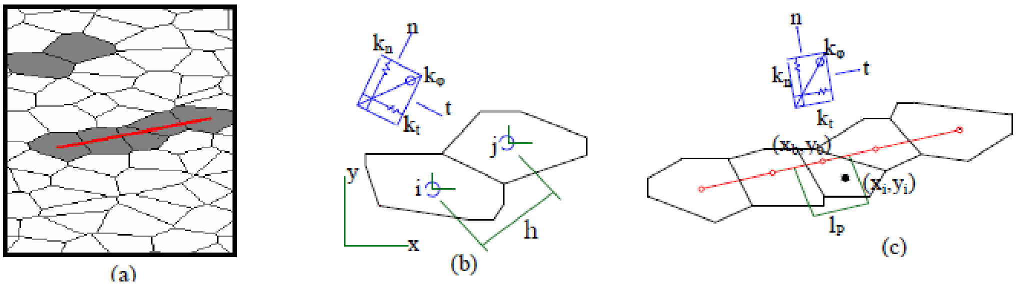


Fig. 1. RBSM modeling of concrete structure; (a) Meshing of concrete domain with reinforcement; (b) Two concrete cells assembly; (c) Reinforcement and bond model.

4. MATERIAL MODELS

Fracture criterions in rigid body spring model is based on the average stresses acting normal and tangential to the particle interface. The criterion is therefore rather simply constructed, which is, uni-axial stress-strain relationship can be introduced into the individual spring.

4.1 Concrete Model

The local stiffness k_n, k_t and k_φ are set to approximate the elastic properties at the continuum level [11]. Normal springs are set to represent tensile and compressive properties of concrete. The tangential spring represents the shear transfer mechanism for concrete. The shear strength is assumed to follow the Mohr-Coulomb type criterion with the tension and compression caps. For cracked interfaces a softening branch given by Saito 1999 [16] is utilized after shear stress reaches the yield strength.

(1) Concrete in compression

The behavior of concrete in compression includes pre-peak and post-peak stage as shown in Fig. 2a. Up to compressive strength, the behavior is non-linear, which is modeled as parabolic curve [17]. After the peak, the linear softening branch is assumed and when the strain exceeds ultimate strain, the stress remains constant.

(2) Concrete in tension

The behavior of concrete in tension is assumed to be linear elastic up to tensile strength. When tensile stress reaches tensile strength, cracks will appear and tension softening model [18] will be applied as shown in Fig. 2b, and tensile fracture energy will be calculated based on the instructions given in JSCE guidelines for concrete 2007.

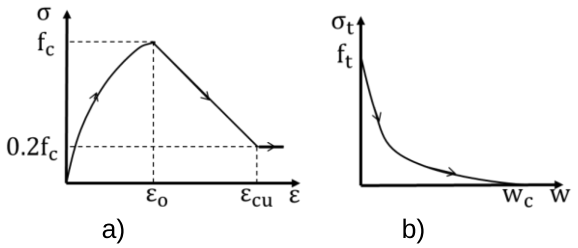


Fig. 2. Concrete model: a) Concrete in compression; b) Concrete in tension

4.2 Reinforcement Model

(1) Steel

Each reinforcement element is explicitly modeled using a series of one dimensional beam elements with axial, shear, and flexural rigidities. Thus, two translational and one rotation degrees of freedom are defined at each beam end. The material stress strain relation for steel reinforcement bar is idealized as bilinear elastic as shown in Fig. 3. The reinforcement is connected to the concrete particles elements through linkage elements, which provides a load transferring mechanism between the beam node and concrete particle computational point [14]. Each linkage element consists of nonlinear zero length link spring (Fig. 1c). One of the link nodes is attached to the reinforcement, while the motion of the other link is rigidly constrained to the generalized displacement of the associated concrete computational point.

Moreover, when slip occurs at the interface between concrete and steel, the bond stress τ_{in}, which is decomposed into shear bond stress τ parallel to the steel bar and radial stress σ_r orthogonal to the steel bar [19], will appear at the same time as shown in Fig. 4.

The shear bond stress τ will be determined from the modified model originally proposed by Shima et al. [20] (Fig. 5) while the radial stress σ_r is calculated from the shear bond stress based on the value of angle α, which varies from 50° – 55° [19]. In this research, the value of α will be taken as 50°. After calculating the radial stress, the radial force, which will be assigned to concrete at the surrounding area of tensile steel as shown in Fig. 6, will also be determined.

$$\begin{aligned} \sigma_r &= \tau.\tan\alpha \\ f_r &= \sigma_r.D \end{aligned} \tag{1}$$

where: σ_r is radial stress (MPa); τ is shear bond stress (MPa); f_r is radial force (N); D is steel diameter (mm).

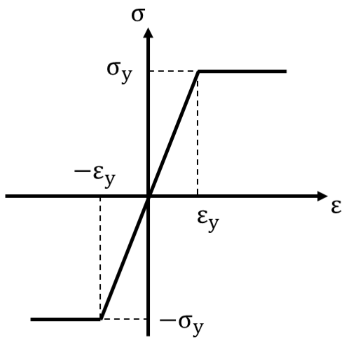


Fig. 3. Stress-strain curve for steel

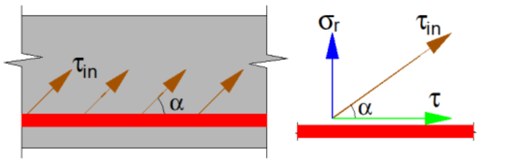


Fig. 4. Bond stress at steel/concrete interface

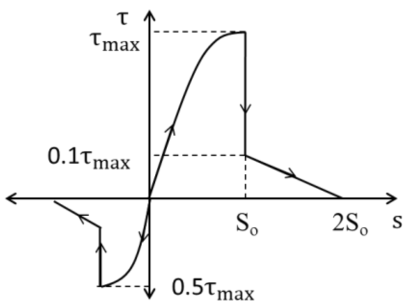


Fig. 5. Modified model of shear bond stress

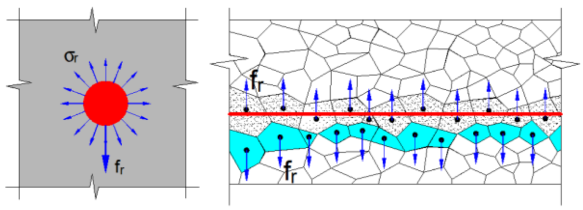


Fig. 6. Radial stress and radial force

(2) Fiber reinforced polymer (FRP)

The behavior of FRP is linearly elastic until it gains the tensile strength and ruptures suddenly. The bond at the FRP/concrete interface plays a crucial role in the behavior of FRP beams, especially when cracks occur and slip reverses, the bond strength will be seriously deteriorated, which is one of the main reasons that lead to premature failure of FRP beams. In this research, the bond model proposed by Sato et al. [21] (Fig. 7) and the bond deterioration model [22] will be utilized. In the bond deterioration model, the bond strength equals zero at crack position and increases gradually to 70% of the original bond strength at a distance 30mm from crack location then after 110mm from crack location, the original bond strength will be applied which will be replaced by simplified 70% of the maximum original bond strength (Fig. 8).

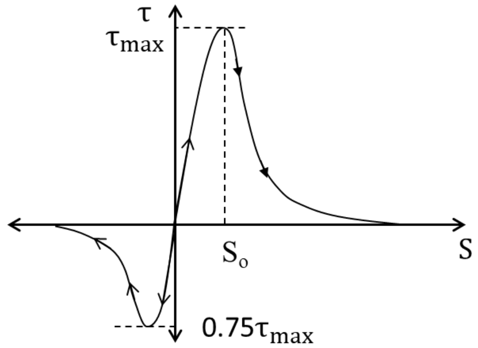


Fig. 7. Bond stress-slip model for FRP/concrete interface

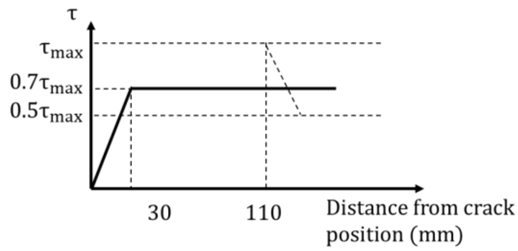


Fig. 8. Bond deterioration model

5. RESULTS AND DISCUSSIONS

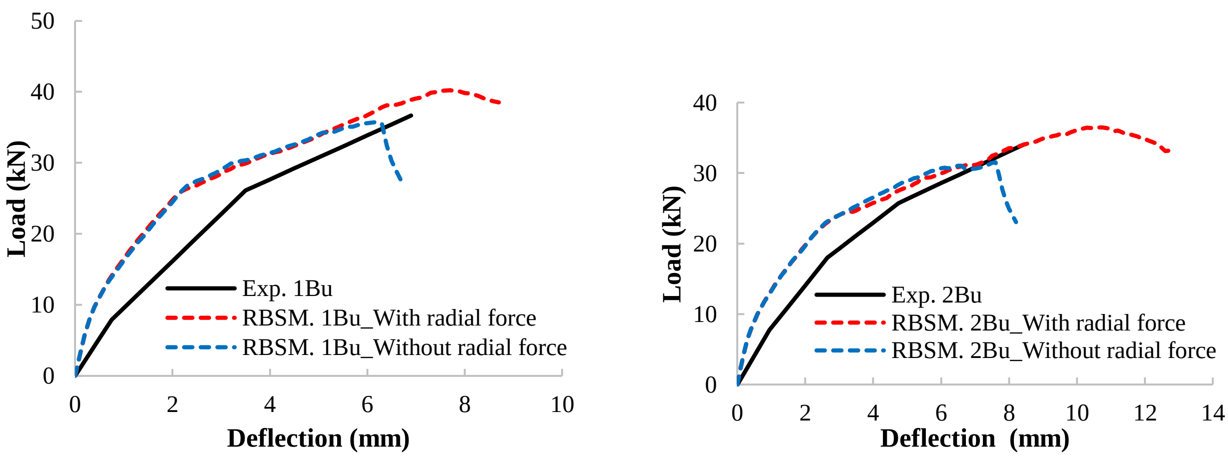
The comparison of results between experiment and numerical simulation including failure mode, ultimate load, load – deflection curve, strain distribution along FRP plate at ultimate load are presented in Table 3, Fig. 9 and Fig. 10.

As can be seen from the Table 3, all the specimens simulated by using the code developed by the authors failed by concrete cover separation, which is the same mode in experiments. In Fig. 11a and Fig. 12a, crack pattern of beams analyzed by RBSM program is demonstrated. From this figure, it is obvious to recognize that RBSM program can simulate relatively well concrete cover separation failure mode of FRP strengthened RC beams while the delamination also -

Table 3 Comparison of ultimate load and failure mode

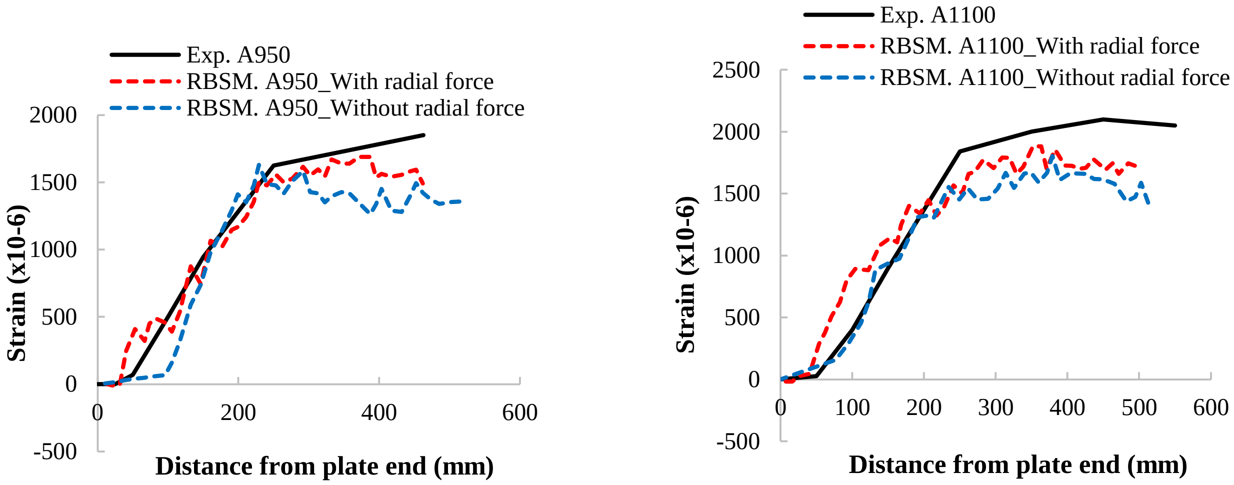
Ref.	Specimen	Failure mode			Ultimate load (kN)			δ(%)
		Exp.	RBSM. (With radial force)	RBSM. (Without radial force)	Exp.	RBSM. (With radial force)	RBSM. (Without radial force)	
[6]	$1B_u$	CCS	CCS	IC	36.5	40.229	35.748	10.22
	$2B_u$	CCS	CCS	IC	34	36.463	31.541	7.24
[7]	A950	CCS	CCS	IC	56.2	57.59	56.905	2.47
	A1100	CCS	CCS	CCS	57.3	61.34	56.176	7.05

Note: *Exp.* is experiment; *RBSM* is numerical analysis using rigid body spring model; *CCS* is concrete cover separation; *IC* is intermediate crack induced delamination; *δ(%)* is the difference of ultimate load between experiment and simulation with radial force.



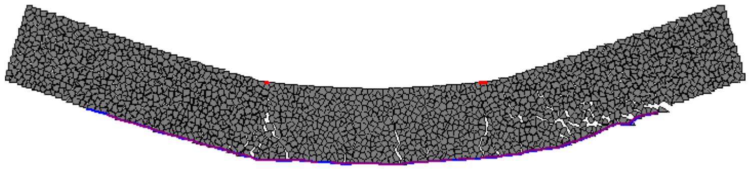
a) b)

Fig. 9. Load - deflection curve: a) Beam 1Bu; b) Beam 2Bu



a) b)

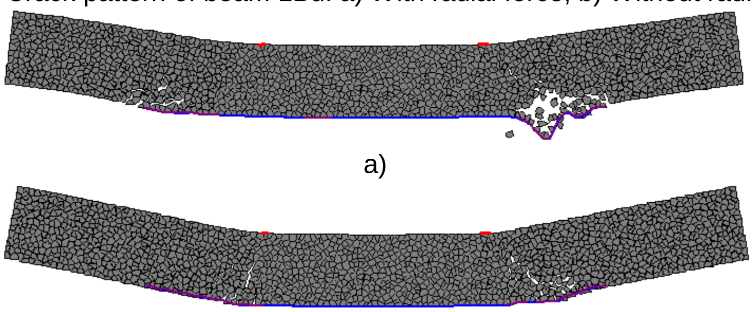
Fig. 10. Strain distribution at the end of FRP plate at failure load: a) Beam A950; b) Beam A1100



a)

b)

Fig. 11. Crack pattern of beam 1Bu: a) With radial force; b) Without radial force



a)

b)

Fig. 12. Crack pattern of beam A950: a) With radial force; b) Without radial force

occurs at the end of FRP plate and at internal reinforcement level then spreads to the middle of the beam. In addition, Fig. 11a and Fig. 12a also show that RBSM program can simulate crack locations, crack propagation as well as the ripping off of concrete in detail on the geometry of the beam, which is an advantage of this method. However, the author could not compare the crack pattern between simulation and experiment due to the lack of this data in the experiment. This problem will be solved in the near future.

Furthermore, the ultimate load between experiment and analysis is also compared and it shows quite good agreement while all the differences are almost under 10% (Table 3). Series 1 [6] and series 2 [7] was conducted to study the effect of shear span and the bond length of FRP plate respectively to the behavior of FRP strengthened RC beam. In series 1, shear span was increased from 300mm in beam 1Bu to 340mm in beam 2Bu and results from both simulation and experiment showed the decrease in the ultimate load from 40.229kN to 36.463kN and from 36.5kN to 34kN respectively. In series 2, the bond length of FRP plate was increased slightly from 950mm in beam A950 to 1100mm in beam A1100 and results from both simulation and experiment showed the increase in the ultimate load from 57.59kN to 61.34kN and from 56.2kN to 57.3kN respectively. Therefore, it can be concluded that results from simulation by RBSM program perform the same trend and reflect fairly well the behavior of FRP beam as in experiment.

In addition, load-deflection curve (Fig. 9) as well as strain distribution along FRP plate at the ultimate load

(Fig. 10) show good agreement between experiment and analysis.

6. CONCLUSION

In this study, rigid body spring model (RBSM) was used to analyze concrete cover separation failure mode of FRP strengthened RC beams with the consideration of radial stress caused by tension steel. To verify the program, some specimens collected from other journals were simulated, then the results from experiment and analysis such as failure mode, ultimate load, load -deflection curve and strain distribution along FRP plate at ultimate load were compared. Through those, some conclusions can be withdrawn as below:

(1) RBSM can be used as a very good numerical approach for simulating premature failure of FRP strengthened RC beams.
(2) Good agreement on failure mode and loading capacity has been found between experiment and numerical simulation.
(3) The results from simulation show a little higher stiffness and it will be investigated in further study.

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