UNIVERSITI PUTRA MALAYSIA

BOND SLIP MODEL OF INTERFACE BETWEEN CONCRETE AND FIBER-REINFORCED POLYMER PLATE USING FINITE ELEMENT

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By

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Master of Science

BOND SLIP MODEL OF INTERFACE BETWEEN CONCRETE AND FIBER-REINFORCED POLYMER PLATE USING FINITE ELEMENT

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March 2014

Chair: Farah Nora Aznieta Binti Abdul Aziz, PhD.

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The bond between Fiber Reinforced Polymer (FRP) plate and concrete surface has shown significant effect on the behavior of strengthened Reinforced Concrete (RC) beam. Therefore, an Intermediate Crack (IC) debonding resistance which depends on the interface between FRP plate and the concrete surface remains as the main concern in designing RC beam strengthened with FRP plate. This research is to develop the bond slip model between the interface of FRP plate and concrete surface and to validate the model by carrying out experimental pull-out test. In the experimental works, two types of FRP installation have been used, namely Externally Bonded (EB) and Near Surface Mounted (NSM) methods. The sizes of FRP plate that were used for both methods were (width (mm) x thickness (mm)): 10x 1.2 , 10x 2.4, 10x3.6, 20x1.2 , 20x 2.4, 30x1.2 , 30x 2.4 and 30x3.6. A total of sixteen samples were subjected to the pull-out test and the results were added with the existing published data to develop the new proposed bond slip model, which was then applied into the finite element model of RC beam strengthened with FRP plate. For validation purposes, comparison of IC debonding resistance was made between the pull-out test using a new bond slip model and the existing bond slip model derived by Seracino *et al*. (2007a). It was found that the pull-out test with the new bond slip model achieved very close results as compared to the bond slip model by Seracino *et al*. (2007a). On the other hand, comparison was also made in terms of IC debonding resistance between the experiment and finite element model of RC beams strengthened with FRP plate. The IC debonding resistance was determined from modeling of Bodin's work by using the new bond slip model for EB method. The results show that the maximum percentage difference of IC debonding resistance obtained from finite element to the experimental results is 7.78 and 24.9 percent for beam P2 and P5.Even though the difference are not close, the model still can prove that the new bond slip model is suitable to be used in prediction of IC debonding resistance for RC beams strengthened with FRP plate.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Sarjana Sains

MODEL IKATAN LINCIR TERHADAP PERMUKAAN ANTARA KONKRIT DAN GENTIAN POLIMER BERTETULANG MENGGUNAKAN ANALISIS UNSUR TERHINGGA

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Ikatan antara plat gentian polimer bertetulang(FRP) dan permukaan konkrit mempengaruhi sifat yang ada pada rasuk konkrit bertetulang. Parameter yang menjadi keutamaan dalam rekabentuk rasuk konkrit bertetulang yang diperkuatkan dengan plate FRP ialah ketahanan nyahikatan retakkan pertengahan (IC) yang mana dipengaruhi oleh ikatan antara permukaan konkritdan plat FRP. Kajian ini dijalankan untuk menerbitkan model ikatan lincir FRP dan permukaan konkrit yang akan dibandingkan dengan keputusan eksperimen. Dalam ujian tarikan, dua kaedah pemasangan plat FRP pada blok konkrit yang dikaji adalah ialah ikatan luaran (EB) dan ikatan luaran (NSM). Saiz plat FRP yang digunakan bagi kedua-dua kaedah ialah(lebar(mm)xtebal(mm)): 10x1.2 , 10x 2.4, 10x3.6,20x1.2 , 20x 2.4,30x1.2 , 30x 2.4, 30x3.6. Sebanyak 16 sampel digunakan dalam ujian tarikan ini.Data-data dikumpulkan daripada ujian tersebut ditambah kedalam data yang telah diterbitkan oleh penyelidikan terdahulu dan dianalisis bagi menghasilkan model ikatan lincir yang baru.Model ikatan lincir tersebut kemudiannya diaplikasikan dalam analisis kaedah unsur terhingga bagi sampel model ujian tarikan untuk menguji keberkesanan model tersebut.Perbandingan telah dibuat antara model ikatan lincir yang baru dengan model ikatan lincir yang telah diterbitkan oleh Seracino *et al.* (2007a).Perbandingan itu menunjukan bahawa model ikatan lincir yang baru menghasilkan keputusan yang lebih tepat berbanding model ikatan lincir yang dihasilkan oleh Seracino *et al.* (2007a).Model baru ikatan lincir diaplikasikan pula pada analisis unsur terhingga bagi rasuk konkrit bertetulang yang diperkuatkan dengan kaedah ikatan luar (EB) oleh plat FRP bagi kerja yang dilakukan oleh Bodin *et al.* (2002).Analisis dijalankan dengan melihat kepada peratus perbezaan nilai ketahanan nyahikatan pertengahan (IC) daripada model terhadap nilai experimen.Keputusan menunjukkan bahawaperbezaan peratusanmaksimum ketahanan nyahikatan (IC) diperolehi daripada kaedah unsur terhinggakepada keputusaneksperimenadalah7.78dan 24.9peratus bagi rasuk P2danP5.Walaupunperbezaannya tidak dekat, model ini masihboleh membuktikan

bahawamodelbaru ikatan lincir ini sesuaiuntuk digunakan dalamramalan ketahanan nyahikatan pertengahan (IC)untuk rasuk yang diperkukuh dengan plat FRP.

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I certify that a Thesis Examination Committee has met on (24 March 2014) to conduct the final examination of Mohd Amirul Bin Mohd Snin on his thesis entitled "Finite Element Bond Slip Model for FRP-to-Concrete Interfaces" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Deterioration is a process that every structure has to undergo, in which the structures lose their strength and this would lead to unsafe conditions for user. Hence, strengthening or repairing is required to improve the stiffness, ductility and strength of the structures. Apart from deterioration due to environmental effect, there are many other reasons the structures particularly concrete need to be repaired and strengthened including an increase of road users in case of a bridge, and underestimated design and change of building function (Amer and Mohammed, 2009). Apart from that, Toatanji and Ortiz (2001) and Fan *et al.* (2006) reported that the major cause of concrete structure deterioration is corrosion of reinforcement. Strengthening is actions taken onto damaged buildings, which are intended to restore the structural strength to the original level. Such strengthening involves actions such as rebuilding of cracked structure elements, stitching of structures across cracks by using steel reinforcement on concrete faces and covered by cement mortar, or grouting of cracks using cement or epoxy like adhesive materials which are stronger than mortar and have tensile capacity. The structure can be assured of its capability to maintain its performance level by examining it following the schedule of maintenance process. Technician needs to assure load carrying capacity, durability and function or aesthetic appearance achieve the standard requirement.

The conventional repair techniques of concrete structures are cement grout, ferrocement cover, and section enlargement. Thanoon *et al.* (2005) investigated the cement grout techniques by using non-shrink premixed high strength cement grout, in which the cement poured into the enlarged space extends the exposed reinforcement. This technique is presented in Figure 1.1 showing the fine crack across the reinforced steel bar. The cement grout was filled into the 50mm width of groove. Romualdi (1998) and Iron (1987) introduced the ferrocement cover method, which is described as a type of thin composite material made of cement mortar reinforced with wire meshes. In this method the ferrocement is coated onto the damaged concrete as shown in Figure 1.2as used by Thanoon *et al.*(2005).The steps of applying this technique consist of removing the concrete from the crack affected zone with the help of a concrete chisel and hammer. After that a layer of wire mesh and a layer of skeletal are fixed with the ordinary reinforcement of the slab. Another conventional strengthening method is called section enlargement, in which the placement of formwork is on the top or bottom ofthe existing structural member to achieve the desired section properties and performance. This method can only be done if sufficient space is available for enlargement of the structural member (Banu and Taranu, 2010). This section enlargement method can be performed either by adding the new reinforcement and concrete layer at the bottom or at the top of the structural members (Oehlers and Seracino, 2004). Figure 1.3 presents the section enlargement method with Figure 1.3(a) showing a damaged slab and Figure 1.3(b) showing an additional reinforcement steel and roughened surface of the slab ready to be casted with new concrete.

The strengthening technique known as Externally Bonded (EB) method as shown in Figure 1.4 has been well established since 10 years ago. Naderpour *et al.*(2008), Amer and Mohammed (2009), and Jumaat and Alam (2010) have investigated the effect of using EB method on reinforced concrete (RC) structures. They claimed that the flexural or shear capacity of RC structures will increase by installing Fiber Reinforced Polymer (FRP) plate using EB method. This technique consists of the steel plate or FRP plate glued onto the surface of concrete using strong epoxy. Service limits in FRP reinforced concrete elements such as deflection, crack width and crack spacing are directly influenced by the bond properties of the reinforcement in the concrete. EB method merely uses a side of FRP plate bonded to a concrete surface. With the aim to maximize the use of FRP plate strength, two sides of FRP plate bonded to concrete is expected to increase the strength of the RC structure. In response to use two side of FRP plate, Blashko (2003) introduced this method by investigating merely on the behavior of adhesive failure. Seracino*et al.* (2007a) investigated this technique on the behavior of interface between concrete and the plate. Authors named this technique as the Near Surface Mounted (NSM) method which involves grooves made on the surface of concrete as shown in Figure 1.5 (a) and then the FRP plate is inserted into these grooves and glued with epoxy as shown in Figure 1.5(b).

In the design of strengthened concrete structure either using EB or (Near Surface Mounted)NSM method, Intermediate Crack (IC) Debonding is an important mechanism to determine the increase in flexural capacity of the beam (Oehlers and Seracino 2004). IC debonding is the propagation of interface intermediate cracks towards the plate end as shown in Figure 1.6(Seracino *et al.* 2007b). Whenever a crack intercepts a plate, the high strain concentrations at the intercept are relieved by the IC interface cracks shown. These IC interface cracks continue to propagate as the intermediate crack width s_{cr} increases under flexure until they spread uncontrollably causing IC debonding resistance P_{IC}. The IC debonding resistance depends on the bond between concrete surface and FRP plate, which is associated to the interface shear and slip of the two. The interaction of interface shear and slip is known as bond slip. The bond slip depends on the glued surface area of FRP plate on the concrete. The larger area of bonding will decrease the maximum shear stress in bond slip and increase the IC debonding resistance (Lamanna *et al.*, 2004).The pull-out test is the most convenient and well accepted method to predict the IC debonding resistances and bond slip for concrete strengthened with FRP. Teng *et al.*(2002), Oehlers and Seracino (2004) have agreed that the IC debonding resistance of pull-out test is a lower bound to the IC debonding resistance of reinforced concrete member. Chen and Teng (2001) and Seracino *et al*. (2007a) used pull-out test to derive the generic equation of IC debonding resistance, from which the IC debonding resistance of structure strengthened with FRP plate can be estimated.

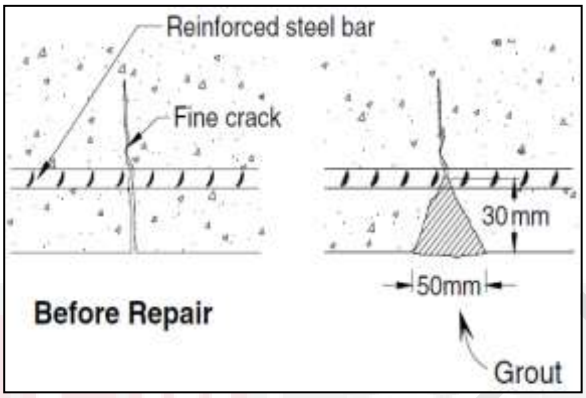

Figure 1.1 : Grout pouring technique (Thanoon *et al,* 2005).

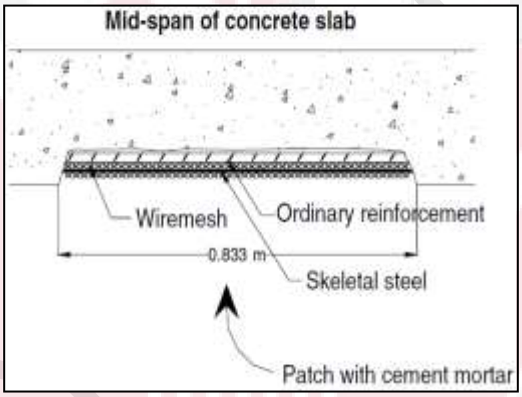

Figure 1.2 : Ferrocement layer technique (Thanoon *et al.,* 2005).

a) b)

Figure 1.3 : Section enlargement: a)crack pattern before repair; b)roughened surface and steel provided. (Banu and Taranu, 2010).

Figure 1.4 : EB Method of FRP plate (Thanasis *et al.*, 2001)

(a) (b)

Figure 1.5 : NSM method of FRP plate (Alkhrdaji and Thomas, 2006).

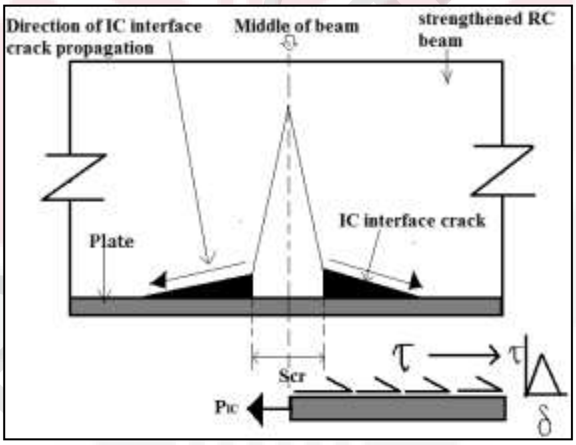

Figure 1.6 : IC Debonding Mechanisme (Oehlers *et al.*, 2007).

1.2 Gap of Research

As mentioned earlier, pull-out test is the most convenient way of determining the IC debonding resistance and bond slip of FRP strengthened beam. However this cannot be translated directly in the modelling of pull-out test, especially to model the bonding between FRP plate and concrete. The bond slip model occupies two important equations such as maximum shear stress and slip. Several bond slip model that have been published before are by Dai *et al.* (2013), Wu and Jiang (2013), Seracino *et al.* (2007a), Chen and Teng (2001), Hiroyuki and Wu (1997), Tanaka (1996), and Maeda *et al.* (1997). All of them except Seracino *et al.*(2007a) have published bond slip model only for EB method. In previous work, Bodin *et al.* (2002) and Lu *et al.* (2005) modeled the bonding between FRP plate and concrete using bond slip model based on tie member analogy proposed by Clement (1987) and Chen and Teng (2001) respectively but those bond slip models are only applicable for FRP strengthened beam using EB method.

Hence Seracino *et al.* (2007a)derived a new bond slip model which can be used for both EB and NSM methods by considering the effect of concrete strength. However, the derivation of bond slip model by them included 22 pull-out test samples data where only a sample of EB method was used and the rest were NSM method samples. They included the size of plate properties and concrete strength in deriving their bond slip model. This research will propose a new bond slip model by taking into account factors such as Young's modulus of plate, concrete strength, plate area and plate depth. By considering all these parameters, it is predicted the maximum shear stress and slip from the new equation will give a close result to the real condition. The closer result of maximum shear stress and slip from new equations to the real experiment will produce more accurate result of IC debonding resistance equation to the experiment.

1.3 Objectives of Study

The aim of this research is to develop the bond slip model of pull-out test, and RC beam strengthened with FRP plate. In order to achieve this aim, the following objectives are outlined:

1. To propose a new bond slip model based on the experimental results from the pull-out test by taking into account the properties of FRP plate.
2. To verify the new bond slip model with existing model derived by Seracino *et al.* (2007a) using finite element method.
3. To validate the new bond slip model in the modeling of strengthened Reinforced Concrete (RC) beam.

1.4 Scope of Study

The scope of the study is limited to the following aspects:

1. The bond slip model was derived by considering properties of plate size, concrete strength and Young's modulus of the plate.
2. The maximum shear stress equation was derived based on 42 samples of pull-out test collected from previous studies and experimental works in this study.
3. The ranges of parameters used in deriving maximum shear stress in the research are tabulated in Table 1.1.

Table 1.1 Parameter range of maximum shear stress equation

Parameters	Range
Plate depth	0.167-30 (mm)
Plate width	1.2-100 (mm)
Young's modulus of plate	32700-425100 (MPa)
Concrete strength	19-57.6 (MPa)

4. The maximum slip equation was derived based on 165 samples of pull-out test collected from previous studies and current experimental works.
5. The range of parameters used in derivation of maximum slip equation are tabulated in Table 1.2.

Table 1.2 Parameter range of maximum slip equation

Parameter	Range
Plate depth	0.083-30 (mm)
Plate width	1.2-100 (mm)
Plate young's modulus	22500-425100 (MPa)
Concrete strength	18.9-69.1 (MPa)

1.5 Flow of Works

This section shows the flow of works of the current research as illustrated in Figure 1.7.

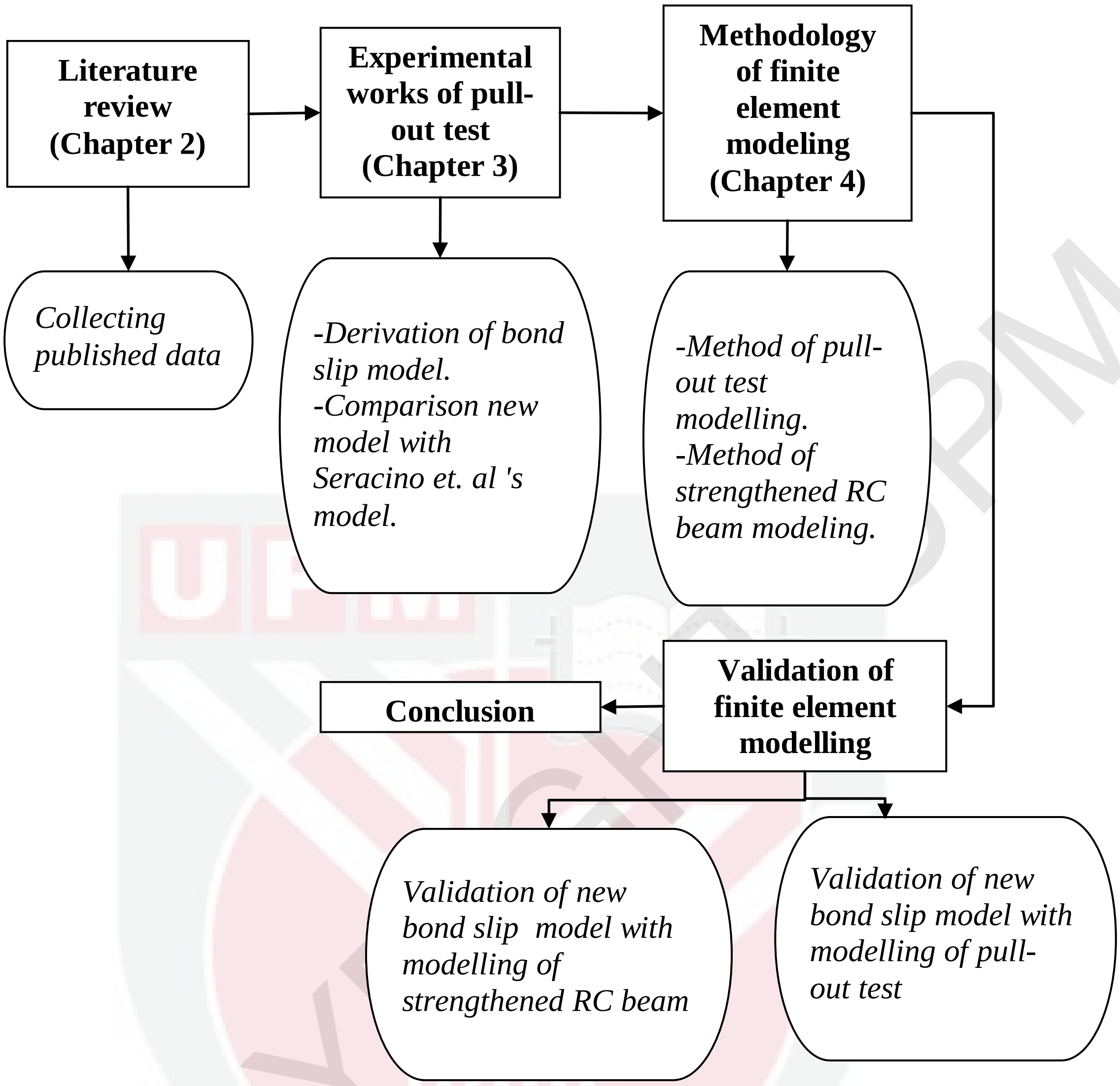

Figure 1.7 : Flow of works

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