UNIVERSITI PUTRA MALAYSIA

MECHANICS BASED SOLUTION FOR PREDICTING DEFLECTION AND ULTIMATE LOAD OF ORDINARY AND PLATED-REINFORCED CONCRETE BEAMS

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By

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Chair : Assoc. Prof. Ir. Raizal Saifulnaz Muhammad Rashid, PhD
Faculty : Engineering

Most design codes available today use full-interaction moment-curvature analysis to determine the deflection and moment capacity of reinforced concrete (RC) beams. This has been achieved by calibrating design equations with hundreds of lab tests to ensure their validity. While this has worked well for steel reinforced RC structures, the derived design equations cannot be used for RC structures with different types of reinforcement material. Alternatively, mechanics-based methods that take into consideration the partial-interaction behavior between the reinforcement and adjacent concrete, and also the size and shape effect of the concrete in compression can be used. The main objective of this study was to develop mechanics-based solutions for RC beams and CFRP plated RC beams to determine their deflection and ultimate load carrying capacity. The results from the mechanics-based methods were compared with the experimental results of three RC beams and three CFRP plated RC beams that were subjected to a point load at mid-span. A comparison between the analytical results and experimental results showed a good agreement between the deflection and ultimate load results for the RC beams. For instance, the difference between the theoretical and experimental ultimate loads for the RC beams considered was merely 0.92%. Good agreement was also observed in the recorded strains in the reinforcement steel at the center of the beam. However, for the CFRP plated beams, the results derived from the mechanics-based solution indicated an early yielding of the reinforcement steel which caused poor correlation of the results at higher applied loads. For example, the theoretical and experimental ultimate loads varied by about 34%. This was attributed to the fact that the strain in the CFRP plate was assumed to remain constant once the intermediate crack (IC) debonding strain was achieved; however, in reality the strain in the plate kept building up until debonding of the plate took place. A parametric study that allowed for shear stresses to develop in the plate after the IC debonding strain was achieved showed a better correlation with the experimental results at higher applied loads for the deflection and ultimate load carrying capacity (difference in ultimate load being less than 5%).

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

SOLUSI BERASASKAN MEKANIK DALAM MERAMALKAN PESONGAN DAN BEBAN MUKTAMAD RASUK KONKRIT BERTELULANG BIASA DAN BERSALUT

Oleh

EL-ZEADANI MOHAMED HASSAN HAMAD

Julai 2019

Pengerusi : Prof. Madya Ir. Raizal Saifulnaz Muhammad Rashid, PhD
Fakulti : Kejuruteraan

Kebanyakan kod reka bentuk yang terdapat pada hari ini menggunakan analisa momen-lengkungan momen interaksi penuh dalam menentukan kapasiti pesongan dan momen rasuk konkrit bertetulang (RC). Ini telah dicapai dengan membuat persamaan reka bentuk kalibrasi dengan beratus-ratus ujian makmal untuk memastikan kesahihannya. Walaupun ini telah berfungsi dengan baik untuk struktur RC bertetulang keluli, persamaan rekabentuk yang diperolehi tidak boleh digunakan untuk struktur RC dengan jenis bahan tetulang yang lain. Selain itu, kaedah berasaskan mekanik yang mengambil kira tingkah laku separa interaksi antara tetulang dan konkrit bersebelahan, dan juga kesan saiz dan bentuk konkrit dalam mampatan boleh digunakan. Objektif utama kajian ini ialah untuk membangunkan penyelesaian berasaskan mekanik untuk rasuk RC dan CFRP bersalut RC rasuk untuk menentukan pesongan mereka dan keupayaan membawa beban muktamad. Hasil daripada kaedah berasaskan mekanik dibandingkan dengan hasil eksperimen yang diperoleh daripada tiga rasuk RC dan tiga CFRP rasuk RC bersalut yang tertakluk kepada beban titik pada jarak pertengahan. Perbandingan antara keputusan analisis dan keputusan eksperimen menunjukkan persetujuan yang baik antara pesongan dan keputusan beban akhir bagi rasuk RC. Contohnya, perbezaan antara eksperimen dan teori untuk rasuk RC diangarkan hanya 0.92 %. Persetujuan yang baik juga diperhatikan dalam tegangan yang direkodkan dalam keluli tetulang di pusat rasuk. Walaubagaimanapun, bagi rasuk bersalut CFRP, keputusan yang diperoleh daripada penyelesaian berasaskan mekanik menunjukkan keluaran awal keluli tetulang yang menyebabkan hasil korelasi yang lemah pada beban yang lebih tinggi. Sebagai contohnya, eksperimen dan teori beban muktamad berubah-rubah kira-kira 34 %. Hal ini disebabkan oleh fakta bahawa ketegangan dalam plat CFRP diandaikan kekal berterusan sebaik sahaja ketegangan peleraian ikatan (IC) dicapai; namun, pada hakikatnya ketegangan dalam plat terus membina sehingga peleraian ikatan plat berlaku. Kajian parametric yang dilakukan membenar tegasan ricih untuk berkembang di dalam plat selepas ketegangan peleraian ikatan (IC) dicapai

menunjukkan kolerasi yang lebih baik dengan hasil eksperimen pada beban yang lebih tinggi untuk pesongan dan beban muatan muktamad (perbezaan beban muktamad adalah kurang dari 5 %).

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Declaration by graduate student

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LIST OF ABBREVIATIONS

AFRP	Aluminum fibre reinforced polymer
CDC	Critical diagonal crack
CFRP	Carbon fibre reinforced polymer
Ck	Crack
EB	Externally bonded
FRP	Fibre reinforced polymer
GFRP	Glass fibre reinforced polymer
IAE	Integral absolute error
IC	Intermediate crack
LVDT	Linear variable differential transducer
NSM	Near surface mounted
PE	Plate end
RC	Reinforced concrete
Sp	Support

LIST OF SYMBOLS

A_c	cross-sectional area of concrete
A_{link}	cross-sectional area of steel links
A_r	cross-section area of reinforcement
$(AE)_c$	axial rigidity of concrete
$(AE)_r$	axial rigidity of reinforcement
b	width of the beam
b_p	width of the plate
B	bond-force
B_{IC}	intermediate crack bond-force
B_{max}	maximum bond-force
c	concrete cover
c_d	half depth of tension stiffening prism
C	cohesive component of the Mohr-Coulomb failure plane
d	effective depth of the beam
d_{asc}	depth of the concrete ascending zone
d_c	depth of the compression zone
d_{NA}	neutral axis depth
d_p	distance to the plate from the neutral axis
d_{pr}	diameter of the concrete prism/cylinder
d_{rc}	distance to the compression reinforcement from the neutral axis
d_{rt}	distance to the tensile reinforcement from the neutral axis
d_{soft}	depth of the concrete softening zone
D	deformation of the concrete top compression fibre

D_{ax}	axial contraction of the concrete prism
D_{mat}	axial contraction of the concrete material
D_{wdg}	axial contraction caused by sliding of the wedge
$d\delta/dx$	slip-strain
EI_{uncr}	uncracked flexural rigidity
E_c	concrete elastic modulus
E_r	reinforcement elastic modulus
E_{sh}	strain-hardening modulus
f_c	concrete compressive strength
f_{cc}	peak compressive stress of confined concrete
f_{CFRP}	fracture stress of carbon fibre reinforced polymer (CFRP)
f_{co}	peak compressive stress of unconfined concrete
f_{ct}	concrete tensile strength
f_{GFRP}	fracture stress of glass fibre reinforced polymer (GFRP)
$F_{r\text{-}cr\text{-}p}$	force in reinforcement to cause primary cracks
f_{tsp}	splitting tensile strength of concrete
f_y	yield stress of reinforcement
$f_{y\text{-}link}$	steel links yield stress
h	height of the beam
h_{cr}	height of the crack
h_r	depth of the reinforcement from the crack apex
L	length of the beam
L_{cr}	length of the cracked region of the beam
L_{crit}	critical length
$L_{crit\text{-}p}$	critical length of plate

$L_{crit\text{-}rt}$	critical length of reinforcement
$L_{db\text{-}p}$	length of EB plate debonded region
L_{def}	half-length of the concrete element/segment
L_p	reinforcement failure plane / perimeter of reinforcement
L_{plate}	plate length
L_{pr}	length of the concrete prism/cylinder
L_{wdg}	length of concrete softening wedge
L_u	length of the uncracked region of the beam
M	moment
M_{app}	applied moment
$M_{cr\text{-}FI}$	full-interaction cracking moment
$M_{cr\text{-}FI\text{-}p}$	full-interaction cracking moment of a plated beam
M_{pr}	primary cracking moment
M_{serv}	applied moment under serviceability conditions
$M_{u\text{-}pp}$	ultimate moment of a passively prestressed segment
P	point load
P_{asc}	concrete force in the ascending zone
P_{avg}	average load
P_{mat}	concrete material force
P_c	concrete force
P_{cc}	concrete compressive force
P_{IC}	intermediate crack debonding force
P_r	reinforcement force
$P_{r\text{-}p}$	axial force in reinforcement after a primary crack has formed
$P_{r\text{-}s}$	axial force in reinforcement after a secondary crack has formed

P_{rt}	reinforcement tensile force
P_{soft}	concrete softening force
P_u	ultimate load
P_y	reinforcement yield force
r	concrete ductility factor
s	segment width
$S_{exp-max}$	maximum experimental crack spacing
$S_{exp-mean}$	mean experimental crack spacing
$S_{exp-min}$	minimum experimental crack spacing
S_{link}	spacing between steel links
S_{pr}	primary crack spacing
S_{slide}	sliding capacity of the concrete wedge
S_{theo}	theoretical crack spacing
t_p	thickness of the plate
u_c	concrete displacement
u_r	reinforcement displacement
V_c	concrete shear capacity
w	crack width
α	angle of the concrete wedge
Δ_{wdg}	slip of the concrete wedge
Δ_d	Lateral slip
Δ_L	Longitudinal slip
Δ_{fract}	reinforcement fracture slip
Δ_{max}	maximum slip at the crack face
Δ_{pr}	reinforcement slip to cause primary cracks

Δ_r	reinforcement slip at the crack face
$\Delta_{r\text{-}p}$	reinforcement slip relative to crack face after a primary crack has formed
$\Delta_{r\text{-}s}$	reinforcement slip relative to crack face after a secondary crack has formed
Δ_y	reinforcement slip to cause yielding
δ	slip
δ_1	slip corresponding to τ_{max}
$\delta_{db\text{-}p}$	total deformation of the plate associated with debonded region
$\delta_{db\text{-}RC}$	longitudinal deformation of RC beam within L_{db} at the level of prestress
δ_{max}	maximum reinforcement slip
$\delta_{max\text{-}p}$	plate maximum reinforcement slip
δ_{mid}	deflection at mid-span
δ_p	plate slip
δ_{rt}	tensile reinforcement slip
$\delta_{\chi u}$	deflection due to curvature of the uncracked region
ε	strain
ε_{axgl}	axial global strain
$(\varepsilon_{ax})_{pop}$	axial strain in Popovics (1973) stress-strain expression
$(\varepsilon_{ax})_{200}$	axial strain for a 200 *mm* concrete cylinder
ε_c	concrete axial strain
ε_{cc}	strain at peak stress of confined concrete
$\varepsilon_{c\text{-}c}$	concrete strain at the outer most compression fibre
$\varepsilon_{c\text{-}t}$	concrete strain at the outer most tensile fibre

ε_{CFRP}	fracture strain of carbon fibre reinforced polymer (CFRP)
ε_{co}	strain at peak stress of unconfined concrete
ε_{crush}	concrete crushing strain
ε_{fract}	fracture strain
ε_{GFRP}	fracture strain of glass fibre reinforced polymer (GFRP)
ε_{IC}	intermediate crack debonding strain
ε_{mat}	elastic material strain
ε_{pk}	peak elastic strain
ε_{r}	reinforcement axial strain
ε_{RC}	concrete strain at the level of the plate
ε_{wdg}	strain caused by wedge sliding
ε_{y}	reinforcement yield strain
θ	rotation
θ_{pp}	passive prestressed segment rotation
σ	stress
σ_{c}	concrete axial stress
σ_{fract}	fracture stress of reinforcement
σ_{con}	confinement stress
σ_{n}	stress normal to the sliding plane
σ_{r}	reinforcement axial stress
τ	shear stress
τ_{max}	maximum bond shear stress
χ	curvature
μ	concrete cylinder shape factor
η	concrete cylinder size factor

$\varnothing$	bar diameter
$\varnothing_{ten\text{-}reinf}$	diameter of tensile reinforcement
$\varnothing_{comp\text{-}reinf}$	diameter of compressive reinforcement
$\varnothing_{link}$	diameter of shear links

CHAPTER 1

INTRODUCTION

1.1 Background

Oftentimes, engineers are called upon to design structures that fall outside the safety net of most design codes; for example, they might be asked to design a concrete structure with new type of reinforcement material or to develop new design rules that are more accurate in estimating the behavior of reinforced concrete structures. Anyhow, to be able to do so and work outside the bounds of design codes, mechanical models that simulate the actual behavior of reinforced concrete structures need to be developed. These mechanical models can be used to determine the deflection of reinforced concrete (RC) structures or moment capacity by simulating the local and global behaviors observed in practice.

Much of the research on predicting the deflection of RC members (Alwis, 1990; Al-Zaid, Abu-Hussien & Al-Shaikh, 1991; Bazant & Oh, 1984; Bischoff, 2007; Branson, 1965; Castel, Vidal & Francois, 2006; Gilbert, 2007) is founded on the assumption that there is full interaction between the reinforcement steel and the adjacent concrete; this is generally known as Branson's approach (Branson, 1965). Using full-interaction, designers would derive cracked and uncracked flexural rigidities that are calibrated from lab data to obtain effective flexural rigidities used to determine the member's deflection.

The full-interaction method for measuring the deflection of RC structures is heavily dependent on test data derived from the laboratory and does not incorporate the slip between the reinforcement and the bordering concrete surface at a crack; thereby, it does not directly simulate the deflection associated with crack widening.

In 1970, Bachmann published a research paper proposing a new method for quantifying the deflection of RC structures (Bachmann, 1970). In his paper, he explained that the rotation of each individual crack contributes to the overall deflection of the beam; moreover, he also mentioned that the beam should be divided into a cracked region and an uncracked region, and the contribution to deflection of each region should be calculated separately and totaled up to give the final deflection of the beam.

Using Bachmann's approach, numerous researchers (Muhamad, Oehlers & Mohamed Ali, 2013; Oehlers, Muhamad & Mohamed Ali, 2013; Visintin, Oehlers, Muhamad & Wu, 2013; Visintin, Oehlers & Sturm, 2016) have used mechanics-based methods to incorporate the slip between the reinforcement and adjacent concrete and eventually measure the deflection of the RC structure. However, in all of these methods, the concrete in compression was taken to be linearly-elastic and the deflection of the RC structures was measured at service loads only; that is, before to the softening of the concrete in compression.

In addition to measuring the deflection, structural engineers have long recognized the significance of ductility in the design of RC structures. According to Oehlers and Seracino (2004), the ductility of a structure is as important as its strength. The quantification of ductility in reinforced concrete structures relies predominantly on the limit of concrete crushing; therefore, making the procedure more or less straightforward. However, as adhesively plating RC structures using fibre reinforced polymer (FRP) plates has become a well-established strengthening technique, the quantification of the ductility of these strengthened structures is more complex. For instance, using a strain-based moment-curvature design technique, the rotational limit of an FRP adhesively plated RC beam depends on either: (1) the concrete crushing strain ε_{crush}; (2) the plate intermediate crack (IC) deboning strain ε_{IC}; (3) the plate fracture strain ε_{fract}. Using this traditional method of design, it is often found that the FRP plate debonds before the yielding of the tension reinforcement; hence, making the entire structure very brittle (Oehlers, Visintin & Lucas, 2015).

Therefore, a displacement-based design could be employed to which partial-interaction theory is at the heart of it. For instance, according to Oehlers et al. (2015), higher ductility, and consequently, higher strength can be achieved using a displacement-based design instead of a strain-based moment-curvature design.

1.2 Problem Statement

Structural engineering design codes available today (e.g. Eurocodes and ACI) rely on full-interaction assumptions, that is no sliding between the reinforcement and the bordering concrete surface, to predict the ultimate strength of the structural member as well as the deflection and crack width. This is possible by carrying out hundreds of laboratory tests for the steel reinforced concrete and later calibrating the test results with the design equations in the code. However, due to their empirical nature, these design equations can only be applied within the bounds of the tests from which they were calibrated (Haskett, Oehlers, Mohamed Ali & Wu, 2009a; Visintin, Oehlers, Wu & Haskett, 2012; Panagiotakos & Fardis, 2001). This has worked well for steel bars due to their high and constant elastic modulus and their good bond with the adjacent concrete (Oehlers et al., 2017).

However, structural engineers today are frequently asked to find solutions to structural members that make use of new reinforcing materials such as fibre reinforced polymer. This would not be possible by using the design codes available today as that falls outside the safety net of most codes. Furthermore, unlike steel reinforcing bars, FRP bars or plates have a wide range of elastic modulus, typically ranging from 40 GPa to 140 GPa depending on the density of the fibre (Oehlers et al., 2013; Oehlers et al., 2017). In addition, different types of fibre such as glass fibre reinforced polymer (GFRP), carbon fibre reinforced polymer (CFRP), and aluminum fibre reinforced polymer (AFRP) add to the complexity of the problem (Oehlers et al., 2013). Not only that but FRP reinforcing bars and plates also have a wide range of bond characteristics depending on the manufacturing process. Therefore, to carry out laboratory tests to determine the properties of each type of fibre would not be economical and feasible.

Furthermore, much of the research on determining the deflection of RC structures using mechanic-based methods that simulate the slip between the reinforcement and adjacent concrete have focused on measuring the deflection under low loads and prior to the softening of the concrete in compression. However, it is well known that with increased loading, the stress-strain curve of concrete begins to deviate from the linear-elastic line indicating some softening as it ascends to the maximum compressive stress and later a large amount of softening as the stress decreases with increasing strains (descending branch). Furthermore, it is well known that the concrete material property relies heavily on the size and shape of the test specimen (Chen, Visintin, Oehlers & Alengaram, 2014; Chen, Visintin & Oehlers, 2015).

In addition to that, it has become common to strengthen RC beams and slabs by adhesively bonding FRP plates to their tension faces using a strain-based moment-curvature design technique. In this approach, failure often occurs when the IC debonding strain is first achieved in the plate. This sometimes makes plating the RC beam ineffective at the ultimate limit state with the plate often reaching its IC debonding strain prior to yielding of the reinforcement.

Therefore, it becomes important to develop a mechanics-based solution that takes into consideration not only the slip between the reinforcement and adjacent concrete, but also the softening of the concrete in compression, and the size and shape of the concrete specimen. Additionally, using a displacement-based approach, the mechanics-based solution for determining the moment of an adhesively plated beam should take into consideration the member debonding mechanism and the propagation of IC debonding instead of halting the analysis when the IC debonding strains are first achieved in the plate.

1.3 Objectives

This research aims to explore the use of mechanical models for RC structures that simulate the behavior that is seen and measured in practice. Also, the work of this research tries to promote the design of ordinary RC beams and CFRP plated RC beams through partial-interaction analysis rather than the commonly used and well understood full-interaction techniques. Henceforth, the objectives of this research can be summarized as follows:

(i) To develop a mechanics-based solution for predicting the deflection and ultimate load carrying capacity of RC beams by taking into consideration the slip between the reinforcement and adjacent concrete, the softening of the concrete in compression, and the size and shape effect of concrete in compression.

(ii) To develop a mechanics-based solution for determining the deflection and ultimate load carrying capacity of a carbon fibre reinforced polymer (CFRP) plated RC beams while at the same time considering the reinforcement and plate slip, the softening and size effect of the concrete in compression and the IC debonding mechanism of the plated structure.

(iii) To validate the results of the mechanical models developed in (i) and (ii) above with the experimental results determined in the laboratory.

1.4 Scope of Research

This research focuses on the development of mechanics-based solutions for RC beams and CFRP plated RC beams. This basically entails the development of mechanical models for the prediction of the short-term deflection and ultimate load carrying capacity of the RC structures while at the same time simulating the behavior that is seen and measured in practice (e.g. slip between the steel reinforcement and adjacent concrete, softening of the concrete in compression and the size effect of concrete in compression). The results obtained analytically were compared with the experimental results determined in the labortory to verify the accuracy of the models proposed. The experimental program consisted of three ordinary RC beams and three CFRP plated RC beams that were tested under three point bending. Furthermore, from the experimental testing, the midspan reinforcement steel and plate strains, flexural crack spacing, midspan deflection and ultimate load carrying capacity were recorded and compared to those derived from the mechanics-based solution.

1.5 Significance of Research

This research tries to pave the way for the acceptance of the design of reinforced concrete structures using partial-interaction analysis. This is mainly achieved through the development of mechanical models that simulate the slip between the reinforcement and adjacent concrete and takes into consideration the softening of the concrete in compression. With such models that simulate what is actually seen and measured in practice, testing at the member level can be eliminated and the only testing that would be required will be that of a material property such as the stress-strain relationship or bondstress-slip properties. Thereby, this will allow for the rapid development of construction materials as hundreds of lab tests would no longer required. In other words, using mechanics-based solutions; the cost of accepting new materials for design will be reduced immensely.

1.6 Thesis Outline

The thesis starts with an introductory chapter (Chapter 1) stating the background of the project, problem statement, objectives and significance to the discipline. After that, a brief review of the relevant literature is presented in Chapter 2. This includes the concept of slip in reinforced concrete, tension stiffening, shear friction, moment-rotation analysis and discrete rotation deflection.

The methodology used in this study is given in Chapter 3. The experimental setup and testing method are discussed first. After that, the mechanical modeling methodology used to form the analytical solution is explained in detail for both the RC beams and the CFRP plated RC beams.

Moving on, the first part of Chapter 4 covers the experimental results in detail. For instance, the concrete compressive cube and cylinder strengths are presented first. After that, the results from the tensile test on the steel reinforcement are given. The strains in the reinforcement, concrete surface adjacent to the reinforcement and CFRP plate as the test proceeded were recorded and presented accordingly. Also, the load versus midspan deflection response and ultimate load results are given. As for the second part of Chapter 4, it presents the theoretical results derived from the mechanics-based solution, which include the midspan reinforcement steel and CFRP plate strains, crack spacing, midspan deflection and ultimate load carrying capacity of the beams considered in this study.

Chapter 5 covers a comparison between the analytical and experimental results, accompanied with relevant discussion on the results. In addition to that, Chapter 5 also presents the results of a parametric study that was performed on the CFRP plated beam in which the bondstress-slip model was varied to allow for a frictional component. Finally, Chapter 6 covers the conclusion and recommendations for future research.

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LIST OF PUBLICATIONS

Elzeadani, M., Raizal Saifulnaz, M. R., Hejazi, F., Mugahed Amran, Y. H., Jaafar, M. S., Alyousef, R., & Alrshoudi, F. (2019). Mechanics-based approach for predicting the short-term deflection of CFRP plated RC beams. *Composite Structures, 225*, 111169, (Published).

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