FLEXURAL ANALYSIS OF CONCRETE BEAMS LONGITUDINALLY REINFORCED WITH GFRP BARS USING DISCRETE ELEMENT MODEL

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This project is submitted in the fulfillment of the requirements for the award of Master in Civil Engineering

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MAY, 2011

ABSTRACT

This paper presents experimental and analytical study related to the flexural behavior of concrete beams longitudinally reinforced with GFRP bars. The specimens consist of simply supported reinforced concrete beams with two point load. Totally 16 concrete beams includes 8 beams reinforced with steel and 8 beams reinforced with GFRP bars were tested to failure. Flexural capacity of the beam was observed experimentally and analytically. A computer program of cross sectional analysis using discrete element model was developed in this study to determine the flexural capacity of the beams. In addition, available stress-strain model proposed by the other researchers was used in order to simulate the behavior of material in calculation process. Finally, the flexural capacity obtained from analytical calculation was compared to that obtained from the test in term of moment-curvature curves and load deflection curves. The results show that beam reinforced with GFRP experienced larger ultimate load and larger deflection at same load level compared to beam reinforced with steel.

Keyword: Reinforced concrete beams, Glass Fiber Reinforced Polymer (GFRP), Flexural capacity.

ABSTRAK

Laporan ini memaparkan ujikaji makmal dan analisis mengenai sifat lenturan rasuk konkrit yang bertetulangkan polimer bertetulang gentian kaca (PBGK). Spesimen ialah rasuk disokong mudah yang dikaji melalui ujian beban dua titik. Kesemua 16 buah rasuk termasuk 8 buah rasuk bertetulang keluli dan 8 buah rasuk bertetulang PBGK diuji sehingga gagal. Kapasiti lenturan rasuk kemudian diperhatikan melalui ujikaji dan analisis. Perisian computer menggunakan unsur diskrit dibangunkan dalam kajian ini untuk menentukan kapasiti lenturan rasuk. Selain itu, model tegasan-terikan oleh penyelidik lain digunakan untuk simulasi perilaku bahan dalam proses pengiraan. Akhirnya, kapasiti lenturan yang diperolehi dari analisis dibandingkan dengan yang diperolehi dari ujikaji melalui graf momen-lengkungan dan beban-defleksi. Keputusan menunjukkan pada beban yang sama rasuk yang bertetulangkan PBGK mengalami defleksi lebih besar dan memikul beban maksimum yang lebih besar.

Kata kunci: Rasuk konkrit bertetulang, Polimer Gentian Bertetulang Kaca (PBGK), Kapasiti lenturan.

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CHAPTER I

INTRODUCTION

1.1 Introduction

Reinforced concrete is a strong and durable building material that can be formed into various shapes and sizes. Its utility and versatility are achieved by combining the best features of concrete and steel reinforcement. When the concrete are combined together with steel, the steel is able to provide the tensile strength while the concrete which is strong in compression protects the steel to give durability.

In current time in Malaysia, as the demand of steel is higher than production itself making the rule of supply and demand applies and led to the rise of its price. The steel is also has problem regarding corrosion. The usage of fiber reinforced polymer (FRP) composite for concrete applications is relatively a new technology that has a potential to replace the traditional steel reinforcement in construction industry as it has the advantages such as not subjected to corrosion, high tensile strength and low unit weight. But since the mechanical properties and surface deformation of FRP bars are different from the conventional steel reinforcement used, investigation is needed to study the behavior of structures using FRP. This study will focus on investigating the flexural behavior of beams reinforced with FRP to see the material’s ability to resist deformation under static monotonic load.

1.2 Problem Statement

Steel bars have been used as reinforcement for more than 100 years and performed well when combined together with concrete structure. The performance of the reinforcement anyhow will change when it is exposed to aggressive environments such as in watery area. As we know, one of the problems faced in construction industry is the use of steel in construction as it is subjected to rust and leads to corrosion.

The construction technology now has become more and more advanced allowing the development of new technologies or material to replace the old one and also solved some of the problems faced by construction experts. The fiber reinforced polymer (FRP) composite is an alternative to replace the current use of steel as it is rust proof and stronger in terms of stiffness compared to steel.

Since the flexural strength normally control the stiffness of beams, more study is still needed related to the flexural behavior of concrete beam reinforced with FRP as it has different properties from steel.

1.3 Objectives

The objectives of this study are to:

1. To study the flexural behavior of concrete beam reinforced with GFRP bars and compared with beam reinforced with steel.
2. To observe the effect of longitudinal reinforcement ratio, shear reinforcement ratio, and shear span-effective depth ratio to flexural behavior of the beams.
3. To create an analytical model that can predict the flexural behavior of the beams.

1.4 Scope of Study

This study is done to analyze the flexural behavior of concrete beams reinforced with steel and GFRP under static monotonic loading. This study involves laboratory activities, analytical study and flexural analysis. Through laboratory activities, sixteen beams are tested under static monotonic loading until failure. The beams are then analyzed by numerical methods using FORTRAN language. A series of cross sectional analysis using discrete element model was developed in this study. In addition, available stress-strain model proposed by the other researchers was used in order to simulate the behavior of material in calculation process. The results of experimental, analytical and flexural analysis prediction will be summarized in terms of load versus strain, load versus deflection and moment versus curvature curves.

CHAPTER II

LITERATURE REVIEW

2.1 Reinforcement

Reinforcements are a tensioning device in a reinforced concrete structure used to hold concrete under compression. Steel is commonly used as reinforcement bars but this project will also focus on using Fiber Reinforced Polymer (FRP) as reinforcements. By adding such reinforcements, it can:

1. Improve formability
2. Increase strength to density and stiffness to density ratio
3. Increase resistance to corrosion, fatigue, creep and stress rupture
4. Reduce coefficient of thermal expansion
5. Produce higher temperature performance

2.2 Fiber Reinforced Concrete

Fiber reinforced concrete is concrete reinforced with fiber reinforcement. The fibers used can be made from plastic, glass and many other materials. The fiber reinforced concrete become popular in recent years because the resulting concretes are substantially tougher and has greater resistance to cracking and higher impact resistance. The use of fiber reinforced concrete does significantly increase the initial costs, but in the long run it is cost effective as it increased the service life.

2.3 Fiber Reinforced Polymer (FRP)

Fiber Reinforced Polymer (FRP) can be considered as a fairly new material in construction industry, but its numerous advantages have made it very popular. FRP become popular because of some reasons such as stronger than steel, superior corrosion resistance, low unit weight and good fatigue behavior. FRP is also magnetically neutral and makes it become very attractive especially in construction of hospital and airport floor areas, which often require magnetic-free environment. (Thamrin, R., *et. al.,* 2002).

In general, FRP can be classified as composite materials that combine a polymer with reinforcing agents. The polymer matrix can be either thermoplastic resin such as polyester, isopolyester, vinyl ester, epoxy and phenolic that reinforced with fibers such as glass, carbon, aramid or other reinforcing materials. FRP may also contain fillers, additives and core materials added to modify and enhance the final product for structural application.

It is important to study the composition of FRP and their characteristics because it will influence their mechanical properties and performance. Criteria that should be considered in the study include:

1. Type of reinforcement or fiber
2. Percentage of fiber volume by weight
3. Orientation of fiber
4. Type of resin
5. Service conditions

The most common FRP composites use in construction industry contain fibers made of aramid (AFRP), carbon (CFRP) and glass (GFRP). However, this study will focus on using GFRP as the reinforcement bars.

2.4 Glass Fiber Reinforced Polymer (GFRP)

Hollaway, L. (1993) stated that glass fibers is the common name given to a number of mutually soluble oxides which can be cooled below their true melting point without crystallization taking place. They are clear, amorphous solids and fail with typical conchoidal fracture surfaces.

Glass is an amorphous material obtained by super cooling of molten glass. They are produced by the combination of metallic oxide with silica in a chemical reaction. E-glass which is based on alumina-lime-borosilicate composition is extensively used since they are more economic, good chemical resistance, high insulating properties and well-performed in mechanical properties. Another commercial type of glass fiber is S-glass which has higher strength, heat resistance and modulus. S-glass normally being applied in the aerospace industry, which has about one-third stronger than E-glass and composed of 65 % silicon dioxide, 25 % aluminum oxide and 10 % magnesium oxide. (James, A. J., and Thomas, F. K., 1985).

In comparison, glass is generally good in the impact resistance, but higher in weight compare to carbon and aramid. It has an equal or better than the steel in certain forms of characteristics. However, the lower modulus made it need a special design in order to perform well in its applications. Glass Fiber Reinforced Polymer (GFRP) is widely used in the construction and automobile industries. For examples, highway sign and post, manhole cover, aesthetic building structures and commercial roofing. As proven, bridge columns that were wrapped with the GFRP were not shaken during earthquake (Dominick, V. R., 1997).

2.5 History of Glass Fiber Reinforced Polymer (GFRP)

According to Davis, C., the first product manufactured from GFRP was a boat hull, which was manufactured in 1930s using a mould made of foam. One of the most notable GFRP projects ever was completed during the 1950s. The Massachusetts Institute of Technology completed a design of a house that was crafted entirely from GFRP. The carefully designed GFRP house began being constructed in 1956 in the Tomorrowland section of Disneyland. Disney's GFRP house was a popular attraction for a full decade before being destroyed in 1967. After the demolition, the building industry began to employ GFRP in a wider variety of construction applications.

By 1994, the building industry had used almost 600 million tons of architectural fiberglasses to craft a variety of buildings and elements. Its usefulness in repairing and renovating structures and elements crafted from an assortment of material was also recognized. Today, there are numerous companies that specialize in the production of GFRP products. These businesses routinely use GFRP to produce watertight domes, detail sculptures and durable benches. GFRP can also be finished to look like wood, quarried stone and bronze. So, individuals can enjoy the beauty of these more traditional materials without the associated maintenance, added weight and higher price tag.

2.6 Research on Glass Fiber Reinforced Polymer (GFRP)

Studies carried out by other researchers have been conducted related to the application of GFRP rods as reinforcement in reinforced concrete structures. Most of them focused on studying deflection behavior, cracking, bond characteristic and design of reinforced concrete beams using experimental investigation and analytical computation.

Experimental and analytical study was conducted by Thamrin, R., *et al.* (2002) on reinforced concrete beams with FRP rods tested until failure under monotonic loading. The tests were performed on three beams with carbon FRP and one beam with Glass FRP. The results show that flexural capacity of beam using carbon FRP is higher than beam using glass FRP.

Test conducted by Saadatmanesh, H., and Ehsani, M. R. (1991) involves an experimental study for six beams reinforced with different combination of GFRP and steel bars. The results showed that the GFRP bar has a good bond behavior with concrete and they concluded that the used of GFRP bars in reinforced concrete has a great chance to replace steel bars especially in corroded area.

Two simply and three continuously supported concrete beams reinforced with GFRP were tested by Habeeb, M. N., and Ashour, A. F. (2008). The experimental results revealed that over-reinforcing the bottom layer of either the simply supported or continuously supported GFRP beams is a key factor in controlling the width and propagation of cracks, enhancing the load capacity and reducing the deflection.

The load-deflection behavior of eight concrete beams reinforced with hybrid GFRP and steel bars were experimentally and theoretically investigated by Qu, W. J., *et al*. (2009). Comparisons between the experimental results and the predictions from theoretical analysis showed that the models adopted could predict the load carrying capacity, deflection and crack width.

MARC software was used in a numerical study done by Chiew, S. P., *et al.* (2007) to test ten beams strengthened by GFRP. The test was done investigate the flexural behavior of the beams under monotonic load. The experimental results showed that both flexural strength and stiffness of reinforced concrete beams could be increased by such a bonding technique.

A test was conducted by Mohd. Sam, A. R., and Narayan Swamy, R. (2005) on beams strengthened with GFRP to analyze their load carrying capacity, load-deflection, load-concrete strain, load-reinforcement strain, cracking and mode of failure. The experimental results shows that beam reinforced with GFRP bars experienced lower ultimate load, lower stiffness and larger deformation. However, the performance of GFRP beams improved when stainless steel was used as shear reinforcement.

2.7 Stress-Strain Behavior

The strength and stiffness behaviors are dominated by the directional characteristic of fibers and the interaction between the stiff fibers and weaker polymer matrix. Different with the steel which has yield point before failure, FRP do not display yield point except for the AFRP stressed in compression, which is a special case. The stress-strain behavior of the FRP until failure is almost linear as shown in Figure 2.1. Elongation at break is typically a few percent for the GFRP and may reach until 5-10 % for the advanced FRP composites (Dominick, V. R., 1997).

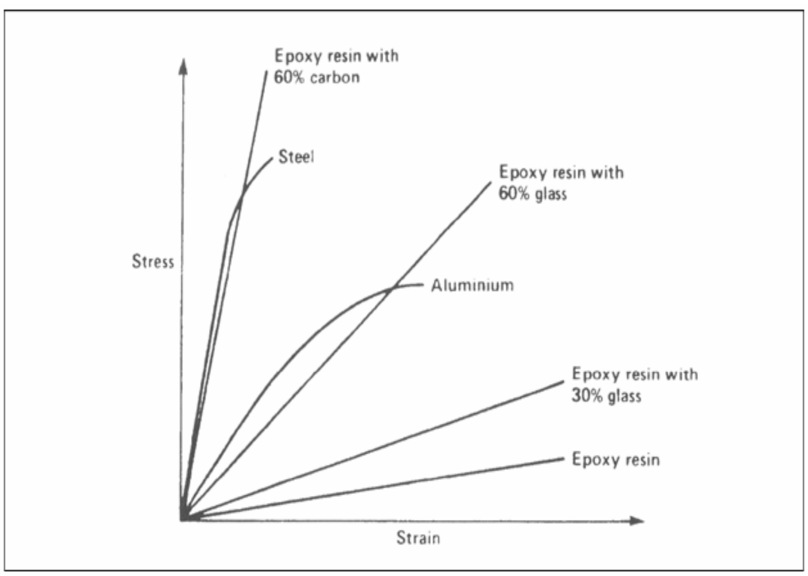

Figure 2.1: Stress Strain Behavior of FRP

(Dominick, V. R., 1997)

2.8 Flexural Analysis

Through this project, flexural capacity of beams under monotonic load is investigated. The load on the beams is gradually increased until peak load and caused flexural failure.

At a low load, the tensile strains and stresses is below the concrete tensile strength the beam is uncracked. As the load is increased, the tensile stress in concrete reaches the tension strength and developed cracks. When the load on the flexural members is further increased the concrete strain reaches the limiting value and represents crush of concrete as flexural failure happened. Flexural failure in a beam can occur in two different ways:

1. The reinforcement yields before the concrete reaches its limiting strain in compression. This type of failure is preceded by warnings through increase of deflection and cracks.

2. Concrete compressive strain reaches the crushing strain before the reinforcement starts to yield. This results in crushing of concrete without warnings.

2.9 Discrete Element Method

Nowadays, discrete element method is becoming widely accepted as a method for addressing engineering problems. The use of discrete element method to solve engineering problems starts in the early of 1970s focusing on rock and soil mechanics disciplines. The discrete element method has become an approach for numerical simulation of engineering applications with most approaches to geological and rock engineering problems.

Through this project, flexural behavior is investigated throughout the beam by dividing the cross section into a number of horizontal elements as shown in Figure 2.2 below, and the remainder is done using FORTRAN's language software.

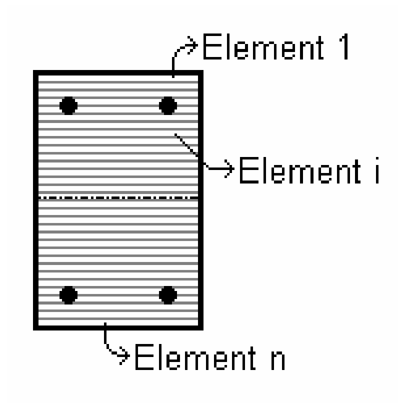

Figure 2.2: Discrete Element Model

(Thamrin, R., *et al*, 2002)

2.10 Research on Discrete Element Method

Studies carried out by other researchers have been conducted related to the used of discrete element model in addressing engineering problems. Most of them focused on studying geological and rock engineering problems.

Masatoshi, U., and Tadahiko, K., (1985) proposed a discrete limit analysis in models consists of rigid bodies and two types of connecting springs, one of which resists the dilatational deformation, while the other one resists the shear deformation. These models are proposed to analyze concrete structures for which the cracking effect may play a vital role in their structural behavior. Verification studies were conducted on the analysis of the shearing type walls.

Experimental and analytical study was conducted by Thamrin, R., *et al.* (2002) on reinforced concrete beams with FRP rods tested until failure under monotonic loading. The experimental tests were performed on three beams with carbon FRP and one beam with Glass FRP and then compared with the results obtained through analytical discrete element model. The results show that flexural capacity of beam using carbon FRP is higher than beam using glass FRP.

Finch, E., *et al*. (2003) developed a discrete element model to observe the difference between weak and strong sedimentary covers deformation in response to basement thrust faulting. The model was used to study the influence of the dip of the basement fault and the strength of the sedimentary overburden on the geometry of the folds generated by block movements in the basement and the rate of fault propagation. The discrete element model used circular particles connected by breakable elastic springs. Particles are bounded until the separation between them reaches a defined breaking strain and the bond breaks. The discrete element model proved to be great help in studying tectonic processes and related geological structures as it has the ability to record the developments of structures with large deformation.

Lorig, L. J., and Hobbs, B. E. (1990) demonstrated the ability to model frictional sliding and stick-slip behavior of faults with the discrete element method for problems where the coefficients of friction of the faults depend on the instantaneous velocity of sliding, as well as on other phenomenological state variables. An extensive verification study was conducted by comparing numerical results for a system of loaded rock masses with analytical results using a number of different constitutive laws. The results of the study show the importance of stiffness of the surrounding rock mass in understanding slip instabilities of single faults.

Brady, B. H. G., *et al* (1986) used discrete element method to analyze an assembly of rock blocks defined in a circular domain of radius 25m and embedded in infinite elastic continuum. After an initial hydrostatic and isotropic loading, the model is subjected to a stress ratio varying from one to four. The results show that rock masses containing sets of non-persistent fractures may indeed be subject to locally varying field stresses. The contours of normal principal stresses plotted after a cycle of loading, unloading and reloading again clearly depict the complicated stress patterns at fracture intersections.

2.11 FORTRAN Program Development

FORTRAN, which originates from the words formula translation, is a high level programming language developed for engineering and science application. Four basic steps in the program development process are as below:

1. Program analysis and specification
   Analyze the problem and specify precisely the input and required output.

2. Data organization and algorithm design
   Determine how to organize data and develop algorithm to process the input and output. Algorithm may be described in a language that resembles those used to write computer programs, called pseudo code. Flowchart may be used for the algorithm.

3. Program coding
   Implement the algorithm in the programming language.

4. Execution and testing
   Check that algorithm and program are correct.

CHAPTER III

RESEARCH METHODOLOGY

3.1 Introduction

This study is conducted to analyze the flexural behavior of concrete beams longitudinally reinforced with steel and GFRP bars subjected to monotonic loading. This study involves both experimental and analytical works. The results of analytical study carried out in this study are then being compared to the results obtained from the experimental test.

3.2 Experimental Works

Laboratory experiment is carried out at the Heavy Structure Laboratory, Universiti Tun Hussein Onn Malaysia (UTHM). Through experimental works, the concrete beams reinforced with steel and GFRP rod is tested using actuator until failure under monotonic loading as shown in Figure 3.1.

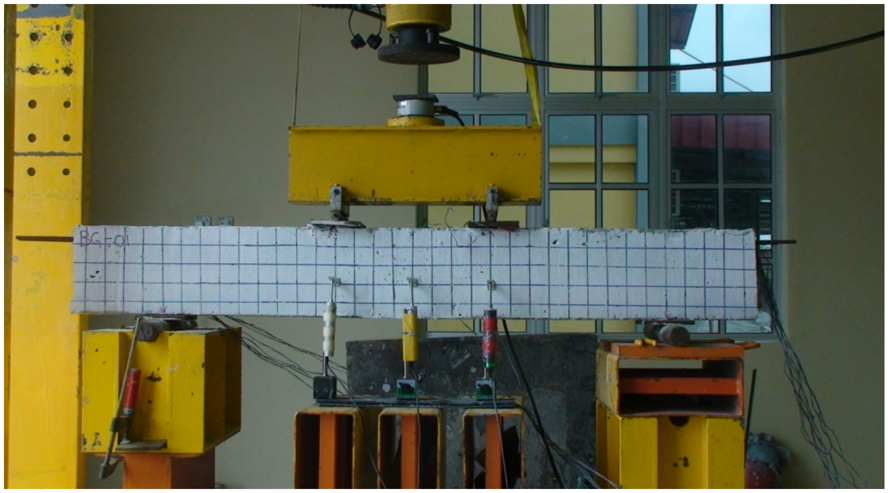

Figure 3.1: Experimental Testing

The test is performed on eight beams with steel bars, then evaluated and compared to similar test performed on eight beams with GFRP bars. Figure 3.2 to 3.9 shows the cross section of beams involved in the experiment.

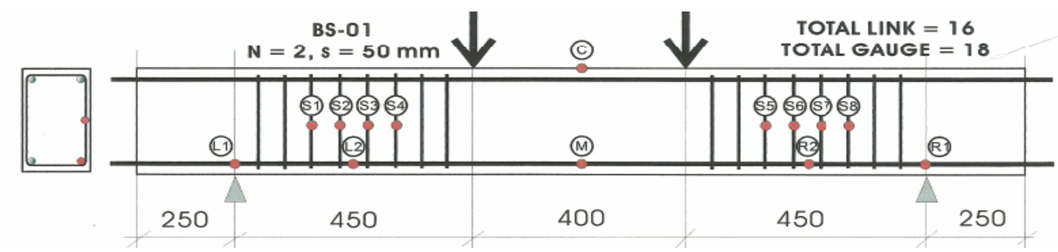

Figure 3.2: Cross Section of Beam (BS-01 & BG-01)

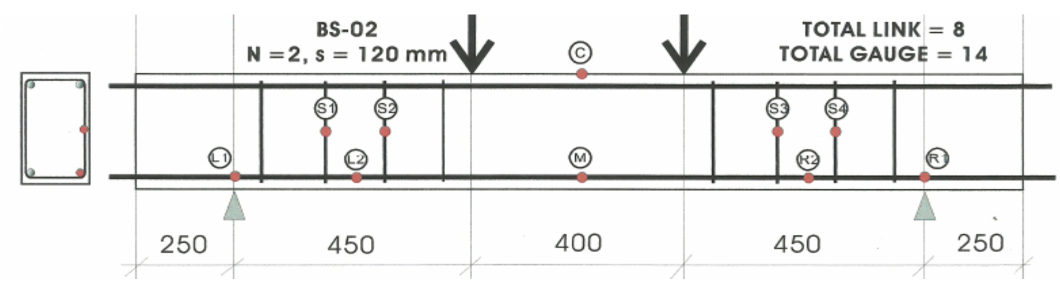

Figure 3.3: Cross Section of Beam (BS-02 & BG-02)

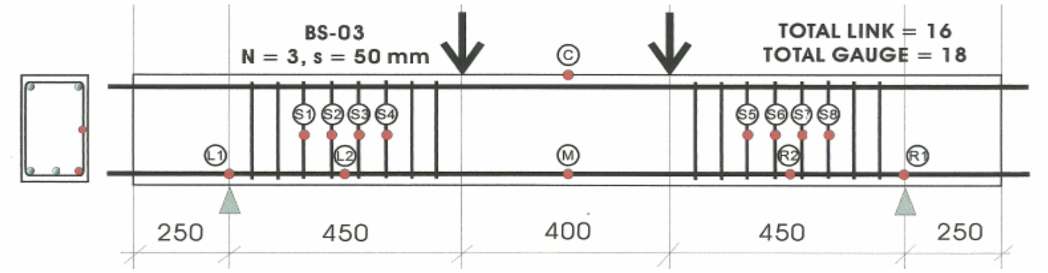

Figure 3.4: Cross Section of Beam (BS-03 & BG-03)

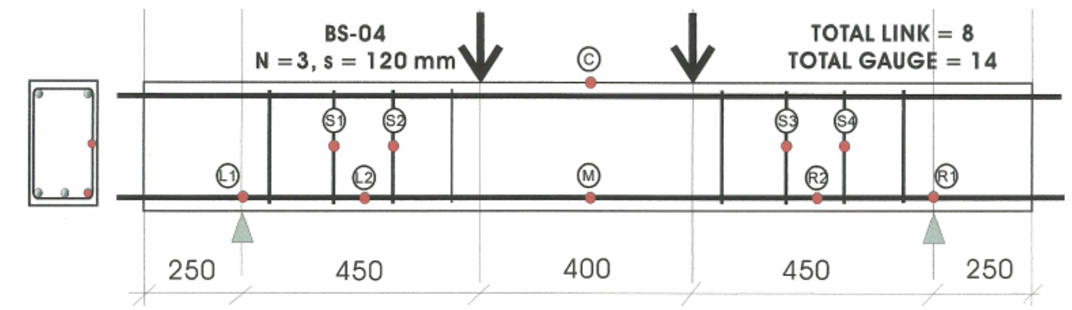

Figure 3.5: Cross Section of Beam (BS-04 & BG-04)

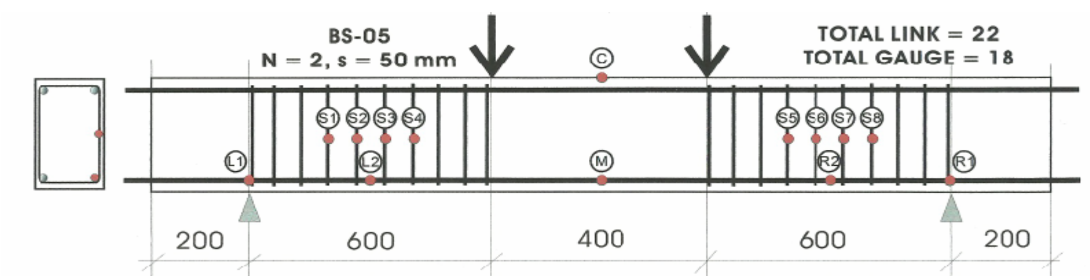

Figure 3.6: Cross Section of Beam (BS-05 & BG-05)

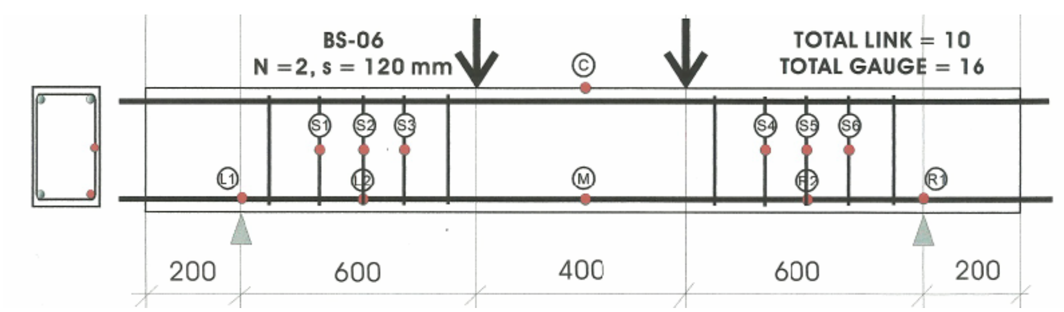

Figure 3.7: Cross Section of Beam (BS-06 & BG-06)

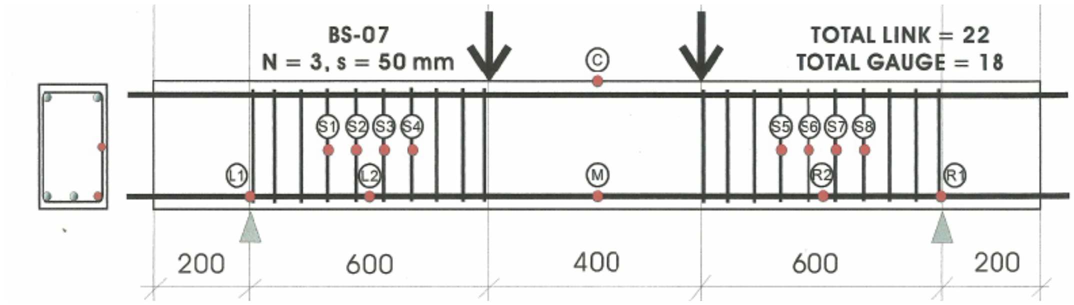

Figure 3.8: Cross Section of Beam (BS-07 & BG-07)

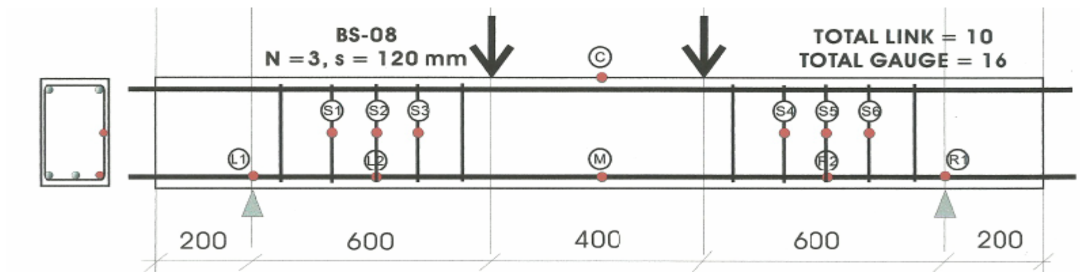

Figure 3.9: Cross Section of Beam (BS-08 & BG-08)

The beams size is 130mm x 230mm with 20mm concrete cover, 10mm diameter reinforcement bars and 8mm diameter stirrup. The data related to the specimens is tabulated in Table 3.1 below.

Table 3.1: Experimental Data

Specimens	f_{cu} (MPa)	b (mm)	d (mm)	h (mm)	a (mm)	a/d	m (mm)	L (mm)	Lh (mm)	L total (mm)	Shear Reinforcement				Longitudinal Reinforcement (Tension)				Longitudinal Reinforcement (Compression)			
											s (mm)	d_s (mm)	ρ_s (%)	f_y (MPa)	N	d_b (mm)	A_s (mm^2)	ρ (%)	N	d_b (mm)	A_s' (mm^2)	ρ' (%)
BS-01											50		1.5		2		157.1	0.6				
BS-02					450	2.1	400	1300	250	1800	120		0.6									
BS-03											50		1.5		3		235.6	0.9				
BS-04											120		0.6									
BS-05											50		1.5		2		157.1	0.6				
BS-06					600	2.9	400	1600	200	2000	120		0.6									
BS-07											50		1.5		3		235.6	0.9				
BS-08	30	130	197	230							120	8	0.6	250		10			2	10	157.1	0.6
BG-01											50		1.5		2		157.1	0.6				
BG-02					450	2.1	400	1300	250	1800	120		0.6									
BG-03											50		1.5		3		235.6	0.9				
BG-04											120		0.6									
BG-05											50		1.5		2		157.1	0.6				
BG-06					600	2.9	400	1600	200	2000	120		0.6									
BG-07											50		1.5		3		235.6	0.9				
BG-08											120		0.6									

3.3 Analytical Study

Discrete element model is used to predict the flexural behavior of reinforced concrete section due to bending. Through this model, the beam section is first divided into a number of horizontal elements, n as shown in Figure 3.10 (b).

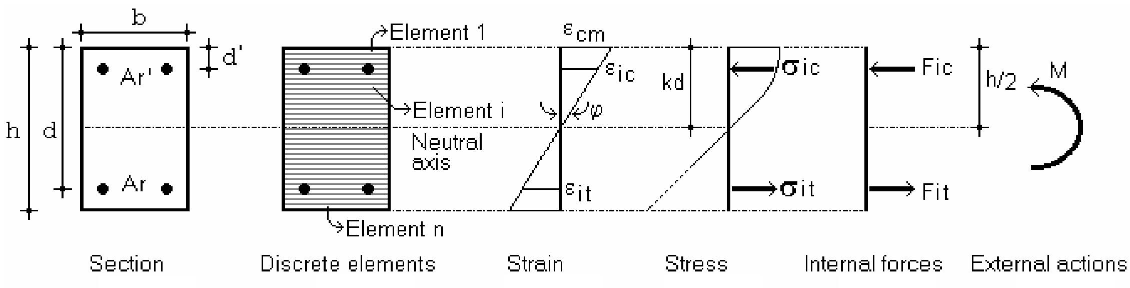

Figure 3.10: Analytical Study
(Thamrin, R., *et al*, 2002)

After this step, there will be n elements on the section that will be identified from the top of section. All of the elements will have the depth h/n and the average strain in each element as shown in Figure 3.10 (c) and can be determined as:

$$\varepsilon_i = \varepsilon_{cm}\frac{n\left(\frac{kd}{h}\right)-i+0.5}{n\left(\frac{kd}{h}\right)} \qquad (1)$$

Where:

ε_{cm} = The strain in top fiber

kd = Neutral axis depth

i =Number of iteration

n = Number of element

h = Height of beam

During the computation process, the strain at the top of concrete fiber, ε_{cm} is a fixed value for each strain increment and the neutral axis depth, *kd* must be assumed at the beginning of increment. Then, the stress, σ_i, in the concrete and reinforcement for each element are found from the strain distribution and the stress-strain relationship which was calculated and assumed before. The forces on the section can be computed from the stresses σ_i, and the areas, A_i of concrete and steel in each element. For elements subjected to compression or tension, the forces written as:

$$F_{ic} = \sigma_i A_i \text{ or } F_{it} = \sigma_i A_i \quad (2)$$

The next step is to check the equilibrium condition of forces acted on the section by using the following relationship:

$$\Sigma F_{ic} + \Sigma F_{it} = 0 \quad (3)$$

If it is not satisfied, an iterative procedure will be started for a new location of neutral axis, *kd* until equilibrium is obtained. From the analysis, the results will be summarized in terms of load versus strain, load versus deflection and moment versus curvature curves. Section properties used for the analysis are; tensile strength for steel, f_y=460MPa, tensile strength for GFRP, f_{fu}=852MPa, compressive strength, f_{cu}=30MPa, modulus of elasticity for steel, E_s=200GPa, modulus of elasticity for GFRP, E_{frp}=57GPa. The analytical procedure can be summarized as Figure 3.11 below.

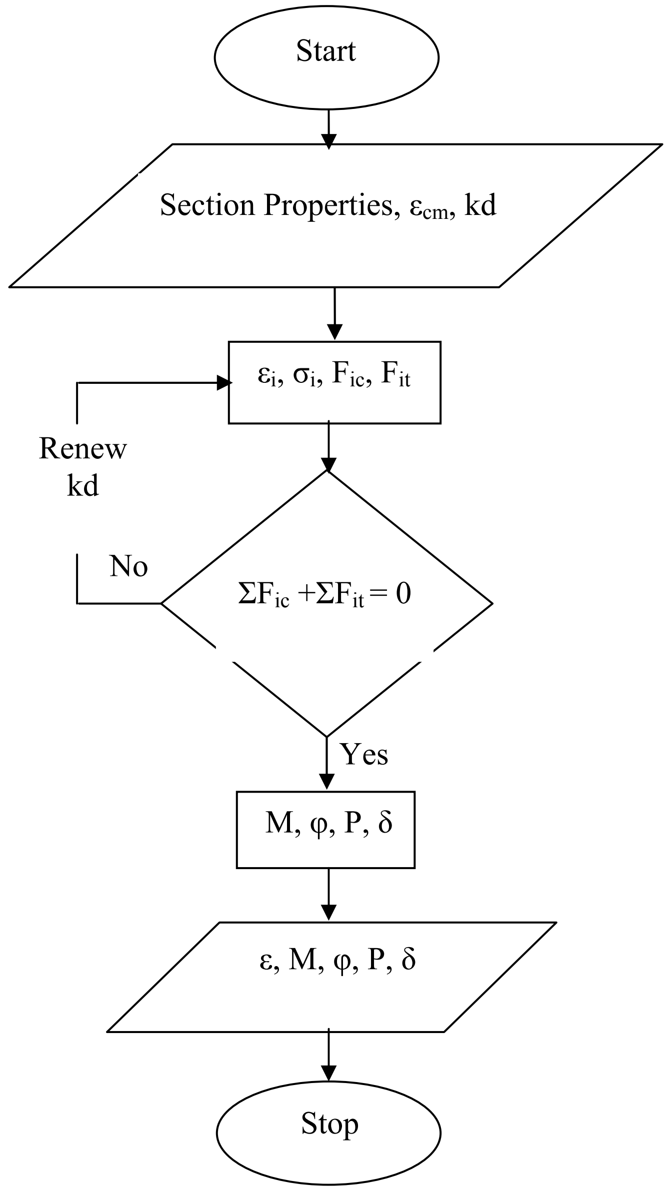

Figure 3.11: Analytical Procedure

3.3.1 Stress-Strain Relationships

Available stress-strain model proposed by Almusallam, T. H. (1997) will be used in order to simulate the behavior of material in calculation process. Figure 3.12 (a) and (b) shows curves for stress-strain model for concrete and steel while Figure 3.12 (c) shows that stress-strain model for FRP bar resulting a linearly elastic up to failure.

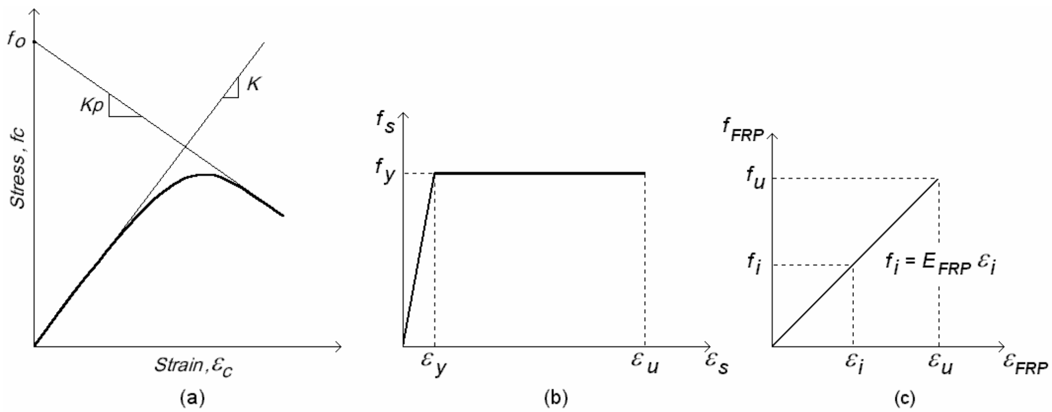

Figure 3.12: (a) Stress-Strain Model for Concrete, (b) Stress-Strain Model for Steel, (c) Stress-Strain Model for FRP

(Thamrin, R., *et al*, 2002)

Equation of stress for concrete is given by:

$$f_c = \frac{(K - K_p)\varepsilon_c}{\left[1 + \left(\frac{(K - K_p)\varepsilon_c}{f_0}\right)^n\right]^{1/n}} + K_p \varepsilon_c \qquad (4)$$

Where:

K = Initial slope of the curve

K_p = Final slope of the curve

f_o = Reference stress

n = Curve shape parameter

Equation of stress for steel reinforcement is given by:

If $\quad \varepsilon_s \le \varepsilon_y \quad f_s = \varepsilon_s E_s$ (5)

If $\quad \varepsilon_s > \varepsilon_y \quad f_s = f_y$ (6)

Equation of stress for FRP bar is given by:

$$f_{FRP} = \varepsilon_{FRP} E_{FRP} \qquad (7)$$

3.3.2 Load-Deflection Relationships

The analytical prediction of load-deflection curve from the moment-curvature distribution along the beam length is found by using the moment-area theorem. The deflection equation given as:

$$\delta = \int_A^B x\varphi dx \qquad (8)$$

Where:

δ=First moment of the area of the M-φ diagram between points A and B, evaluated with respect to B.

φ=Curvature corresponding to each incremental step.

3.3.3 Moment-Curvature Curve

Analytical prediction will produce moment-curvature curve for test beam as shown in Figure 3.13, the curve will illustrate the flexural rigidity of the concrete beams.

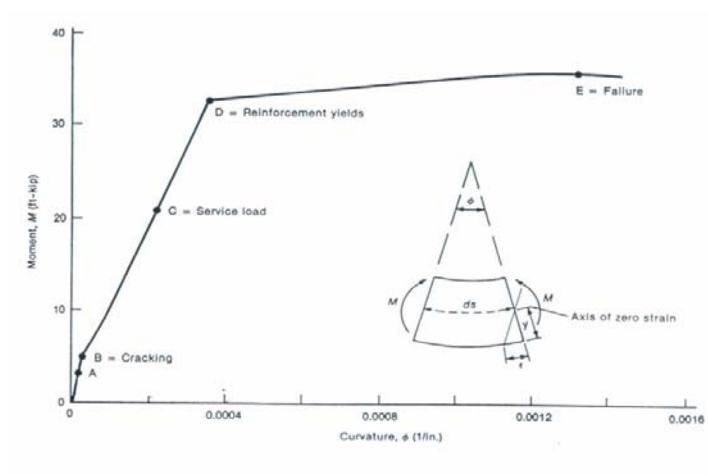

Figure 3.13: Moment versus Curvature Curve for Test Beam (Macgregor, J. G., and Wight, J. K., 2005)

3.4 Flexural Analysis

Trough flexural analysis, the moment required to initiate cracking can be calculated as:

$$M_{cr} = \frac{f_r I_{cr}}{D - k_d} \qquad (9)$$

$$\varphi_{cr} = \frac{M_{cr}}{E_c I_{cr}} \qquad (10)$$

Where:

f_r = Tensile stress

I_{cr} = Moment of Inertia

The equations defining the moment and curvature at the first yield are stated in equation 11 and 12 below:

$$M_y = A_{st} f_y z \qquad (11)$$

$$\varphi_y = \frac{\varepsilon_s \varepsilon_m}{d} \qquad (12)$$

Where:

ε_s = Maximum strain in steel

ε_m = Maximum strain in concrete

The ultimate moment and curvature can be found using equation below:

$$M_u = 0.85 f_{cu} \gamma k_u d b \left(d - \frac{\gamma k_u d}{2}\right) + A_{sc} f_y (d - d_{sc}) \qquad (13)$$

$$\varphi_u = \frac{0.003}{k_d} \qquad (14)$$

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