REHABILITATION OF PARTIALLY-FAILED REINFORCED CONCRETE BEAM BY USING ALUMINIUM COIL

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I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the Bachelor of Engineering (Hons) in Civil Engineering.

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I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged. The thesis has not been accepted for any degree and is not concurrently submitted for award of other degree.

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Dedicated to my beloved family and friends

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ABSTRACT

Strengthening of existing reinforced concrete beams is one of the best solutions applied globally in construction field to partially-failed building elements. This paper presents an experimental study aims to investigate the flexural behavior of reinforced concrete beams strengthened by bolting layers of aluminium coil to the beams' soffit. Beam samples were loaded until they have reached partially-failed condition and strengthened by bolting different thickness of 0.6 mm, 1.2 mm and 1.8 mm aluminium laminates. Then each was tested to failure in four point bending over a clear span length of 1500 mm and one sample was not strengthened with any aluminium laminates and served as a control beam. Test results clearly illustrated the application of aluminium laminates to the tension surface of the reinforced concrete beam has enhanced its ultimate load capacity. It was observed that as the number of layers of aluminium laminates increases, the ultimate load capacity of beams increases accordingly. Therefore, this retrofitting method of construction could be utilized as one of the ways in strengthening partially-failed reinforced concrete beams.

ABSTRAK

Pengukuhan semula rasuk konkrit yang sedia ada adalah salah satu penyelesaian yang terbaik untuk digunakan dalam bidang pembinaan untuk struktur bangunan separa gagal. Kertas kerja ini membentangkan satu kajian bertujuan mengkaji kelakuan lenturan rasuk konkrit bertetulang yang diperkuatkan dengan menggunakan lapisan gegelung aluminium dibawah rasuk. Rasuk dibeban sehingga mereka telah mencapai keadaan separa gagal. Kemudian dikukuhkan dengan aluminium berbeza ketebalan sebanyak 0.6 mm, 1.2 mm dan 1.8 mm. Rasuk kemudian diuji sehingga mencapai tahap gagal. Satu sampel rasuk yang tidak diperkuatkan dengan lapisan aluminium juga diuji sebagai rasuk kawalan. Keputusan ujian jelas menunjukkan penambahan lapisan aluminium ke permukaan tegangan rasuk konkrit bertetulang telah meningkatkan kapasiti beban muktamad. Dapat diperhatikan apabila bilangan lapisan aluminium meningkat, kapasiti beban muktamad rasuk meningkatkan. Oleh itu, kaedah pengukuhan semula ini boleh digunakan sebagai salah satu cara dalam mengukuhkan rasuk konkrit bertetulang separa gagal.

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Ø	Diameter
°	Degree
c/c	Centre to centre
σ	Stress
P	Load
A	Cross sectional area
Ɛ	Strain
∆L	Change in length
L_o	Original Length
d	Effective depth
F_{cc}	Stress in concrete in compression
F_{st}	Stress in steel in tension
A_s	Area of reinforcement
n	Modulus of elasticity transformation coefficient for steel to concrete
I_{cr}	Moment of Inertia of cracked, transformed section
E	Modulus of elasticity
I	Moment of inertia

LIST OF ABBREVIATIONS

RC	Reinforced concrete
AGC	Aluminium Glass Composite
CFRP	Carbon Fibre Reinforced Polymer
LHS	Left hand side
RHS	Right hand side
ACI	American Concrete Institute

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Reinforced concrete (RC) is a composite material made up of concrete which consists of a mixture of Portland cement, sand, aggregates, additives with water and steel reinforcement. Today's in this twenty-first centuries; our city landscape is mainly constructed from reinforced concrete due to its high relative compressive and tensile strength and provides long lifespan with low maintenance cost. This statement is significantly displayed by the icon building, Central Market, Kuala Lumpur which was constructed since year 1930s as wet market and being undergone the adaptive reuse process which transformed its function into handicraft and cultural center which leading it toward to be one of the famous tourists attraction till now.

The design service life of a reinforced concrete structure generally estimated as 100 years. However, in the real case, due to several factors such as weathering, ageing effect, insufficient maintenance and increased external loadings applied to the structures has deteriorated its structural capability. For an instance, formation of cracks on the surface of RC beam has weakened its strength and instigates corrosion to reinforcement which later led to partially or total failure of the structure (Wang J. et al., 2014).

This situation has concern the safety of the public when the condition of the building has deteriorated. In order to solve this issue, method to rehabilitate partially-failed reinforced concrete beam has widely discuss and practice in the construction industry. Therefore, in this chapter, the background, problem statements, objectives, scopes and significance of this research study will be discussed. It will focus on the topics of rehabilitation of partially failed reinforced concrete beam by bolting aluminum coil which served as external plate reinforcement to regain its structural capability.

1.2 BACKGROUND OF STUDY

As a future civil engineer, we are exposed to knowledge regarding the structural behaviour of the reinforced concrete structural elements which included beams, columns, slabs and others. Although the design life span for the reinforced concrete structure is about 100 years, however due to weathering, insufficient maintenance, overloading and other factors, existing reinforced concrete structures may have loss its structural capability before reaching the ultimate designed lifespan. For an instance, the concrete may have expressed its partially failure mode-deflection or formation of cracks on its surface when it has undergone additional loadings to the extent that are not covered in the designed safety factors before the final failure takes place (Alaee & Karihaloo, 2003). Therefore, several strengthening methods should be implemented on this partially-failed reinforced concrete beam before final failure may take places.

One of the most commonly used solutions to implement on partially-failed RC beam is external strengthening as it is convenient to the owner or publics to rehabilitate the existing beam. According to the research study-Flexural strengthening of RC beam by bolted side plates (BSP) that carried out by Siu, Wing Ho in year 2009, bolted a steel plate to the both side of beam was one of the solutions to solve this issue as it would boost up the ductility, shear and flexural strength of the existing beam. It is also provides additional free space for erection of scaffolding which serves as prop support. Instead of placing steel plate on the both side of the beam, it is suggested that fibre reinforced-polymeric composite system can be bolted at the beam's soffit which imitate the sandwich structure to be applied on RC beam to repair partially-failed RC beam (Mosallam et al., 2015).

Thus, in this study has focused on rehabilitation of partially-failed reinforced concrete (RC) beam by bolting aluminium coil to the soffit of the beam which imitates the semi-sandwich structure in order to improve its structural capability to comply with the standard requirement.

1.3 PROBLEM STATEMENT

Flexural strength is the ability of the material to sustain loadings before it reaches partially or totally failure. Our city landscape is mainly constructed from reinforced concrete due to its high relative compressive and flexural strength and provides long lifespan with low maintenance cost.

However, reinforced concrete buildings are often exposed to loading from external surrounding such as vibration of machinery and equipment, wind action, heavy rainfall and others that applied on it (Lee & Barr, 2004). This may lead to decrease in fatigue life of the structure where deflection or cracks may be observed from the structural element which served as a good warning to the owner or publics before it has reached total failure (Ahmed et al., 2014). Therefore, upgrading and strengthening method need to be applied to the partially-failed element to improve its structural performance.

Based on the problem statement, this research study will be focused on the suitability of rehabilitation of partially-failed reinforced concrete beam by bolting aluminium coil beneath the beam to determine whether it can enhance the flexural and other characteristics of the existing beam or not.

1.4 OBJECTIVES

The objectives of this study are:

1. To investigate the flexural behaviour of partially failed RC beam strengthen with aluminium coil on the soffit of the beam
2. To compare the flexural strength between partially failed RC beam strengthen with aluminium coil and conventional RC beam (control RC beam)
3. To determine relationship of load applied to the deflection and pattern of cracking of the reinforced concrete beam

1.5 SCOPE OF STUDY

The principle of this study is to investigate the flexural behaviour of RC beam with sizes 150mm (width) x 200mm (height) x 1500mm (length) strengthen by attaching aluminium coil as external plate reinforcement to the existing beam's soffit. This helps us to determine the ability of aluminium coil to upgrade and reinforce the existing partially-failed RC beam by potentially enhance their load carrying capacity. Several tests will be carried out in order to determine the performance of aluminium coil as external plate reinforcement to the partially failed RC beam.

Concrete compressive test (BS1881: Part 1 16:1983 and ASTM C39-03) is carried out to ensure the compressive strength of the concrete sample is grade 25 at 28 days. The concrete cube is tested until it reached failure and the maximum load achieved is considered as the ultimate load for future strength calculation.

Concrete flexural test is carried out to determine the deflection, flexural and tensile strength of both control RC beam and partially-failed beam bolting with aluminium coil at the beam's soffit under three point loading.

1.6 SIGNIFICANCE OF STUDY

Issues on rehabilitation have been discussed widely in construction industry as alternative for the strengthening method to the existing structure. For an instance, plywood shear walls has been used in conjunction with the unreinforced masonry walls for the purpose of increases the load carrying capacity of the existing structures to withstand the power of earthquake in Los Angeles, USA.

Hence, this study was developed to investigate the suitability of aluminium coil with properties: low density which is just one-third of steel, high strength and excellent corrosion resistant as the alternative materials to be bolted to the beam's soffit to strengthen existing beam. This study will helps in introducing a new alternative material for rehabilitation purpose to the construction industry. As aluminium coil is high in strength to weight ratio, thus it can reduce installation cost where lesser workers will be required in the repairing process and increase the load carrying capacity of the existing structural element. Moreover, this study can be served as a future reference on this issue to upgrade and strengthen the partially-failed structure.

1.7 CONCLUSION

This chapter has significantly outlined the introduction, background and the problem statement, scope and significance of study regarding on rehabilitation of partially-failed reinforced concrete beam by bolting aluminium coil to the soffit of the beam utilising the concept of sandwich structure. The main objectives of the study has been finalised and the next chapter will discuss on literature reviews that portray information of detailed study related to our topics of interest.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter provides background of this research study and analysis of the relationship among differ works. In this chapter, reinforced concrete and its application in construction industry is briefly discussed. Besides that, issues regarding on deterioration of reinforced concrete and method on solving it are being assessed too.

Furthermore, rehabilitation method as one of the effective solution to solve this phenomenon are further discussed in this chapter in order to provide a broader view regarding of my topics of interest-rehabilitation of partially failed reinforced concrete beam by using aluminium plate. Characteristics and properties of an aluminium plate are further examined in order to investigate the suitability of aluminium plate to serve as the external plate reinforcement in strengthening the partially-failed beam. A number of researches on previous literature reviews that portray information of detailed study related to our topics of interest-rehabilitation of partially failed reinforced concrete beam are evaluated. Different strengthening method and their behavioural characteristics will be discussed in this chapter too.

2.2 REINFORCED CONCRETE

Reinforced concrete is a composite material that made from the combination of concrete and reinforcements. According to the book, Making the Modern World: Materials and Dematerialization wrote by Smil (2014), the second largest country, China had utilised approximately 6.6 gigatons of cement in the construction industry for the past three years. This tremendous amount is equal to nearly a hundred years of cement consumption required in United State of America for construction purposes. This incident has clearly portrayed the importance of cement, one of the principal 'ingredients' in concreting infrastructures and buildings to be their first priority compared to other construction materials such as fly ashes and gypsum. With the presence of cement, aggregates, additive with water produce a good performance concrete which are highly preferable in the construction industry.

The existence of reinforcements which is one of the essential components in forming reinforced concrete structures that acts as the backbone have overcame the properties, weak tensile strength of the concrete. The ridges on the external surface of the reinforcing bars called 'deformed' help in providing strong gripping force to the concrete by forming strong bond between them and distributing load between concrete and itself to the below parts of the structure elements. However, reinforcements such as steel bars are vulnerable to corrosion when they are exposed to unfavourable environment such as in the marine environment. In this point of view, presences of waterproof hardened cement paste in concrete and concrete cover with pH 12 and above has solved this problem by creating an alkaline environment and forming a passivity layer of oxide, calcium oxide which helps in prolong the corrosion of the reinforcement in the reinforced concrete structures (Neville, 2011). Thus, the combination of both materials in forming reinforced concrete has provides a longer shelf life and better structural performance to the people.

2.2.1 Application of Reinforced Concrete

Nowadays, in this modern twenty-first century, there is substantial transformation in the design of new buildings and infrastructures which concentrated on economy, environment, safety and aesthetical aspect which aims to minimise resources consumption, environmental and man-made impact. Improved structural performance of concrete, economy and construction processes and energy saving has become the main drivers of leading the transformation of construction industry.

According to the Nikkei (2014), the Japan's leading contractors have discovered solutions to boost up the durability of reinforced concrete structures to exceed a hundred year which is achieving its ultimate designed service life by reducing the opening between particles in concrete. By covering a layer of polyethylene sheet to the surface of hardened concrete structure helps in restraining the evaporation of water during hydration process which lessens the gaps forming in the concrete. In addition, forming concrete with half of the required volume of water added together with specific additives are also one of the best solution to lengthen the lifespan of the structure where cracks is less likely to form. This applied technology is not only enables owners felt relieved from bearing a huge amount of repairing and maintenance cost for the partially-failed reinforced concrete structures in their life, but also ameliorate its structural performance to users.

Due to improved properties of reinforced concrete: higher compressive and tensile strength, it has been widely utilized in construction industry not only in buildings and structural elements like foundation, beams, columns, slabs and others, but also infrastructures like pavement roads, airport runways, bridges, dams, embankments. Earth retaining structures like retaining wall and abutments for bridges and water retaining structures like water tanks are one of the typical usages of reinforced concrete. As it can be casted in various shapes, it is widely used in precast structural components too where it yields rigid members with minimal apparent deflection.

2.2.2 Deterioration of Reinforced concrete

A well-designed reinforced concrete structure is durable and strong. Nevertheless, reinforced concrete buildings are often exposed to cyclic loadings, inconstant pressure, temperature and severe environmental effects that have unlocked the deterioration mechanism of reinforced concrete in the real structure (Zhang et al., 2014). This may lead to the formation of micro cracks and spalling which can be observed from the exterior part which showing its partially-failed characteristics. Although these small anomalies do not influence the serviceability of the reinforced concrete structures in the beginning, however they may threaten the long term structural capability from durability' aspect (Moradi-Marani et al., 2014). In order to counteract with the argument on total failure that may be occurred in the future, it is crucial for us to figure out the main factors leading to the deterioration of reinforced concrete structures and their aftermath. This may help us to select the most suitable remedial actions to be taken.

Climate effects is one of the main causes of deterioration of reinforced concrete structures. In our country, Malaysia, reinforced concrete structures undergo slightly expansion in the day when heated and contraction in the night when cooled. While for reinforced concrete structures in seasonal countries such as Australia, United State, and others may undergo a greater expansion in summer and contraction in wintertime. There would be a change of 17 millimeters for every 30.5 meters of reinforced concrete when they are subjected to a rise or fall of 38 Celsius (Lawrence Grybosky, undated). This thermal differential results in shortening of structural elements when they were in restrained condition. They will experience stress which will then causing them to crack and spall at location at where expansion/contraction joints are absent or in between two adjacent concrete sections. According to Ismail, Muhammad, & Ismail (2010), exposure to the acid rain and other contaminated environment can accelerate the deterioration of reinforced concrete structures too and corrode the exposed reinforcements when the carbonic acid present in acid rain lowered down the pH value of the concrete structure and break down the oxide layer. This eventually led to the total failure at the end when there is no remedial actions applied promptly.

Cyclic loading is one of the causes of deterioration of reinforced concrete structures where they are subjected to repeated loads. Under this condition, they have reached failure mode before achieved the ultimate stresses which are much lower than the elastic limit and absence of plastic deformation in the stress-strain curve. This concept is just similar to the case known as metal fatigue which causes severe damage to the metal component when it has been subjected to repeated bending at the same point consequence impairs of the material and broke at the end. In construction industry, cyclic loading is one of the important elements that engineers required to consider for the designs of offshore structures where much of the loadings exerted on the foundations are derived from the periodic wave action (Byrne B. W., Houlsby G. T., & Martin C. M., 2012). According to Kim, Nam, & Youn (2015), the offshore structures will be undergone 10^8 lateral cyclic loading events in their designed lifetime and found that increased of the number of cycles and loadings indeed increases the lateral displacement at the pile head. This cause the decrease of efficiency of the pile group (Mokwa & Duncan, 2001).

Overloading is one of the roots that weaken the structural capability of the reinforced concrete structures. Additional loads or overloading may be derived from adaptive reuse process where buildings and infrastructures has been undergone transformation without redesign the structural design to comply with the standard requirements. Early dismantling of propping support can result overload cracking when structural elements have not achieved early design strength. This eventually reduces its durability and may threaten safety and health of the public when the structures has achieved total failure mode and collapsed. This is significantly showed by the case which involved collapsing of Skyline Plaza, Virginia in year 1973 due to overloading cracks found around columns during construction process is carried out and led to fourteen deaths and thirty-four injuries. These accidents may be avoided if remedial actions and precautions is taken speedily once partially-failed characteristics is noticed.

2.3 PARTIALLY-FAILED CHARACTERISTICS – SPALLING, LOAD CRACKING AND DEFLECTION

Spalling is classified as one of the signage of pre-structural failure where a large piece or flakes lost at the surface of the reinforced concrete structure. It is caused by high pressure and temperature, sudden hit exerted on it from the surroundings or under design. Under this phenomenon, expansion of materials has occurred and weaken the bond between concrete and reinforcements and break at the end. This action had produced 'pop outs' which force surrounding mortars and aggregates to create shallow conical depression. As a result, severe conditions where total failure may take place when owners do not take any initiatives in addressing this matter promptly. Remedial action such as demolition and reconstructing instead of rehabilitation will be required to apply on failed structures to avoid issues such as collapsing of building that causes losses of lives, welfares and other consequences take place in the future.

According to the book, Properties of Concrete wrote by Neville (2011), formation of cracking which is one of the partial failure characteristics will later lead to the total failure of reinforced concrete structures where durability and strength of the concrete is greatly jeopardised. One of the main factors that causing cracks is overloading that can be derived from live, dead, wind, rainfall, snow load and other sources and exerted on structural members. These members are subjected to axial, lateral loads and bending moments which forming flexural cracks when it has reached its ultimate strength and no longer be able to sustain its load carrying capacity.

According to Gribniak et al. (2013), one of the partially-failed characteristics: deflection is greatly affected by phenomena such as shrinkage and cracking. While according to Vanderbilt, M. D., M. A. Sozen, & C. P. Siess (1963), deflection is influenced by sizes and stiffness's of the structural elements, the types and extent of the loading exerted on it and substandard materials and practices. A lower stiffness' beam creates maximum moments and causes maximum deflections with tremendous increase in curvature at each crack. When the deflection has exceeded the maximum deflection limits which portrays signs like severe spalling, cracks and deflection on the structural elements, serviceability of reinforced concrete structure is greatly jeopardised in term of aesthetical and functional issues (R. I. Gilbert, 2001). It also allows penetration of chemicals into the concrete and triggers corrosion of reinforcements. Besides that, excessive deflection may destroy the adjacent supported structural elements and causing inconvenience to building users. Thus, it is crucial to boost up the structural performance of the reinforced concrete structure by applying several remedial actions in order to reduce the occurrence of total failure in the future and provides safety and health environments to the public.

2.3.1 Demolition

According to the book, Advanced Construction Technology wrote by Chudley & Greeno, (2006), demolition can be classified into two categories: taking down process which is also recognized as partial demolition which involving removal of structural members and demolition process which is the ultimate solving method involving complete removal of a structure when it is dangerous, no functional value or in disastrous and abandoned. Before any demolition process is took place, investigations will carry out to review the case, look out for the weaknesses and determine the best solution in addressing this issue.

For an instance, a reinforced concrete building in Nigeria has uninhabited when its structural elements has begun to display characteristics of partially-failed mode in year 2001 (Olajumoke et al., 2009). Due to its severe condition where serious cracks and deflection occurs in the walls and slabs, its structural capability in the present state is greatly reduced. Thus, consultants have suggested method of demolition and reconstructing structural elements on the basement of the building to regain its structural capability.

While a barn in New York, United State of America has collapsed due to excessive snow load applied on it in the winter storm occurs in year 1999 (Gooch, C. A. & Gebremedhin, K. G., 1999). Investigations have been carried out to determine the main factors that causing the building failure. It was found that a truss which served to support the roof and transmits force in axial direction was damaged due to overloading from snow accumulation on the roof. Consultants have suggested the method taking down process which replaced the damaged one with new trusses.

2.3.2 Rehabilitation

Rehabilitation is defined as the act of reinstate something back to its original state. According to the book, Guide for the Structural Rehabilitation of Heritage Building wrote by (CIB, 2010), buildings or infrastructures with existence of partially failure characteristics, damage after catastrophe such as earthquakes, for adaptive-reuse process and increased load bearing capacity require the action of rehabilitation to be implemented. Rehabilitation works can be classified into two categories: repair which is simply to regain load bearing capacity of structural elements and upgrading or known as strengthening which aims to increase the load carrying capacity of building elements.

Strengthening materials is one of the principal criteria required to consider when rehabilitation method is applied to the structural elements. It must comply with standard requirements. It has to be durable and protect reinforcement, dimensionally stable, good contact bonding between the existing and new retrofitting material and be able to regain the serviceability of the reinforced concrete structural element (Jorge A. Guilar, 1995). Resin is one of the rehabilitation solution which injected to fix cracks and to substitute small amounts of damaged concrete. With the presence of resin, tensile, flexural and compressive strength of the repaired reinforced concrete is greatly enhanced.

2.4 APPLICATION OF REHABILITATION METHOD

Rehabilitation involving activities such as repairs, replacements and improvements. According to Jorge A. Guilar (1995), rehabilitation technique aims to restore, enhance strength, stiffness and ductility of structural members of the reinforced concrete structure. Local strengthening or recognized as internal strengthening is one of the rehabilitation technique implemented which involving material substitution process and helps to increase the stiffness and load bearing capacity of the existing building elements.

Surface preparation is a critical step to take place before applying any remedial actions. For an instance, cleanliness of the surface of the existing building element is highlighted to prevent loose particles attaching to it and lead to the weaken bond formation, shrinkages and other partially-failure characteristics. Then, remedial action will be implemented to addressing problems such as injecting epoxy and resin to crack areas, substituting the buckled reinforcements with a new one, adding reinforced concrete building elements to boost up the out-of plane strength and stiffness and prevent lateral overturning from occurring and etc.

On the other hand, rehabilitation technique also involving external strengthening of the existing structural elements. One of the modification is concrete jacketing which covering a layer of strengthening material to the existing structural element. It is suggested to be applied at three sides or four sides of the elements to provide the best performance. It enables the enhancement of axial, flexural, and shear strength of the old structural element. It also triggers the changes of bending stiffness and moment capacity after jacketing process is applied. Nevertheless, according to the book, Earthquake-Resistant Structures-Design, Assessment, and Rehabilitation wrote by Moustafa (2012), this jacketing application is not advisable to be implemented for beam elements as it will form strong beam-weak column which introduced the issue of structural instability in the structure.

Furthermore, rehabilitation also involving span shortening process where additional support is installed beneath of the existing building element according to the article, Keys to Success: Structural Repair and Strengthening Techniques for Concrete Facilities wrote by (T. Alkhrdaji, 2004). Bolting or adhesive anchoring cast-in-place reinforced concrete members and steel members to it helps to shorten the span, carry and transfers loading to the existing members. Through this rehabilitation method, stiffness and load carrying capacity of the members are greatly advocated.

According to the article, Rehabilitation of the Infrastructure Using Composite Materials: Overview and Application wrote by YA Al-Salloum & T. H Almusallam (2002), epoxy injection has been suggested as one of the rehabilitation method to restore the reinforced concrete building elements to its pre-cracked strength. It forms a stronger chemical bond with the existing concrete which increases its compressive strength when epoxy is injecting to the crack area. Nevertheless, epoxy for crack injection is not suitable for condition where water leakage problem is occurring within the crack areas. In this matter, polyurethane foams with elastomeric characteristics will be applied to cure this issue as it harden within a short time and eliminate the possibility of materials flowing out from the injected crack. It react with the moistures around the crack area and form foam within a short time and expand inside the wall until it is fully covered the void area. Although it does not contribute to the any additional of compressive strength to the existing concrete, but it is practical in our residential application. By applying epoxies or polyurethane foams to crack areas, load carrying capacity of the members can be greatly advocated.

In addition, article, Rehabilitation of the Infrastructure Using Composite Materials: Overview and Application wrote by YA Al-Salloum & T. H Almusallam (2002), external or internal prestressing also recognised as one of the conventional rehabilitation method to restore the strength of reinforced concrete building elements. Article, Overview of external post-tensioning in bridges wrote by T.G. Suntharavadivel & Thiru Aravinthan (2005) have proven that external post-tensioning and plate bonding can improve the structural capability and serviceability of the bridge structures. This method are preferable in the construction industry as it only causes the minimum disruption to traffic during the day and adding the minimum weight to the existing structures compared to other rehabilitation method. For an instance, Condet Bridge in Indonesia which had constructed in year 1989 and undergone retrofitting method by implementing two post-tensioned cable covered in polyethylene tube which provide corrosion resistant to it after five years due to overloading from heavy vehicles. The tendon were firstly anchored by using conventional barrels and wedges near to the pier support. Then, anchorage plate were fixed permanently by using bolts and welding to it and stressing process were begins. After that, all the exposed tendon strands will be sheathed with grease tape to resist to corrosion and provide sealing to the whole post-tensioning system completely. It is proven that the same method has applied to Kemlaka Gede Bridge and has minimized the mid-span stresses in steel beams by 30% to 50% (A. Daly & W. Witarnawan, 2000).

2.4.1 Old and Heritage Building

National heritage is one of the crucial components in a township which symbolized a milestone within the city from the past and will be handed down to the next generation. Malaysia is one of the countries that brimming with cultural heritage which includes the tangible one - historical buildings that significantly displayed their great architectural, structural and historical value to the people. In order to preserve, conserve and lowering the environmental impact of these infrastructures, it is a must to apply an effective method to improve and reinforce them when their structural capabilities does not comply with the requirement due to occurrence of cracking on beams, corrosion and increased of load carrying capacity of the structures (D. Goldar, H. Singh, & M.S.M. Ali, 2005).

According to F. Rangelova, E. Abdulahad, & J. Cenkova (2014), repair or replacement of damaged elements, alterations or additions for adaptive-reuse process required rehabilitation of preservation of historical and cultural heritage. According to the book, Guide for the Structural Rehabilitation of Heritage Building wrote by CIB (2010), the remedial actions taken for old and heritage buildings generally involving addition of compatible materials and reinforcements to increase its load bearing capacity. However, in severe condition, partial demolition will be carried out and reinstalled a new one to transfer adequate loading to adjacent structural elements. There was a case study regarding on rehabilitation technique implemented to foundations of an old building in Lapa, Lisbon by using micro piles executed on each side of the wall system. The existence of these small diameter micro piles helps to support, control settlements and displacements, preserve façade and improve structural and seismic performance of existing building elements (Antunes, T.R.S, 2012).

2.4.2 Overload Building

Reinforced concrete structures can degrade due to overloading and begins to reveal their partially-failed characteristics when they are no longer sufficient to sustain additional loading exerted to them. Thus, preparation such as extensive investigation work included visual inspection, field and laboratory testing on the building will be carried out. Field testing are aims to determine the severity of the building condition, detecting the location and width of cracks and concrete strength by using rebound hammer or other non-destructive tests while laboratory testing are aims to determine average concrete strength of reinforced concrete structural elements with higher accuracy. Detailed evaluating and action taken on strengthening method and materials will then be implemented depends on the severity condition of buildings and infrastructures.

According to the book, Strengthening and Rehabilitation of Civil Infrastructures Using FRP composite wrote by (Hollaway & Teng, 2008), there were real case study regarding on the flexural strengthening of Louisa-Fort Gay bridge and The Carter County bridge in Lawrence, Kentucky, America. Inspection is carried out on location where flexural cracks are present and found that mainly cracks are due to heavily loaded vehicles especially lorries and buses. It is found that five axle lorry weighted 1000 kN have been passed through the bridge. Nevertheless, the load limit is recorded as 712 kN. In order to extend the serviceability of the bridge, it is a must for the bridge to be rehabilitated. It is suggested to mount injection ports in cracks firstly and seal those cracks by using epoxy components through injection port. Then, two-part resin is put on continue with attaching CFRP composite where its strength with 2800 MPa and stiffness value with 150 GPa to the bottom of RC girdles. Lastly, crack monitoring gauges will be mounted directly to the repaired girdles to investigate the effect of composites to the girdle. By applying retrofitting technique instead of replacing a whole new superstructure, it helps the authority to save roughly three hundred thousand dollar.

2.5 ALUMINIUM COIL

Aluminium is third most plentiful element on Earth which constituted approximately eight percent after oxygen and silicone element. Aluminium is unable to stand by itself as a single element. This is because it will react with oxygen easily and form compound recognised world widely as bauxite ore or aluminium oxide trihydrate in their present state. It is later reduced into pure aluminium through smelting process. Once it is purely formed, it will be alloyed with other metal such as iron, zinc, copper and etc. to produce aluminium alloy with different characteristics comply with the demand requirements.

Aluminium is a lightweight material with specific weight of 2.7 g/ cm^3 which is just a one-third of the specific weight of steel metal. This weight to strength ratio has induced aluminium to be the principal material in transportation industry which included air, sea, road and rail as it could contribute to the enhancement of load bearing capacity, energy saving, speed, conservation of number of labors and cost saving. This statement is significantly shows that due to lightweight properties of aluminium, it has replaced steel in the framework structures of a ship in order to lessen the whole weight of the ship and speed up its mobility (B. Liu, R. Villavicencio, & C. Guedes Soares, 2013).

Besides that, corrosion resistance is also one of the properties of aluminium that induced people to consider it as their first priority metallic material compared to steel metal. It is a more reactive metal with high affinity for oxygen in term of their chemical properties where it will form a thin and protective oxide coating layer easily which hindered it from further oxidation. In order to lengthen the corrosion resistance of aluminium, different types of surface treatments such as painting and anodising can be implemented on it.

High strength are also one of the attractive characteristic of aluminium alloy. Some of aluminium alloys are stronger than steel metal. Furthermore, it does not become brittle under low temperature but advocate its tensile strength. According to Adam Lipski & Stanisław Mroziński (2012), tensile strength only reduced by ten percent under temperature range from 25 Celsius to 125 Celsius and achieved roughly seventy-five percent of tensile strength value get from temperature twenty-five percent at 200 Celsius.

Table 2.1: Mechanical properties of Aluminium

Properties	Aluminium (2.0mm)	Steel (1.4mm)
Density (kg/m^3)	2650	7850
Young Modulus (GPa)	72	206
Poisson Ratio	0.33	0.3
Yield stress (MPa)	125	228
Ultimate stress strength (MPa)	257	364
Fracture stress (MPa)	257	272
Fracture strain (100mm)	0.15	0.23
Strength coefficient (MPa)	405	585
Strain hardening exponent	0.16	0.172

Sources: (B. Liu et al., 2013)

In conclusion, these properties of aluminium has induced it to be suited as one of the strengthening material to rehabilitate the partially-failed reinforced concrete beam.

2.6 RESEARCH ON REHABILITATION OF PARTIALLY-FAILED REINFORCED CONCRETE BEAM

In order to deal with partial failure problem that encounters in construction industry, there are a numbers of previous research studies have been carried out regarding on the method of rehabilitation of reinforced concrete structural elements.

Morsy & Mahmoud (2013) have claimed that Carbon Fibre Reinforced Polymer (CFRP) as the external plate reinforcement is an effective solution to improve the structural performance of the reinforced concrete beam. The method of laying full contact for both flexural and shear to the FRP laminate are the most efficient ways where it has an increment of 37.5 % over the unstrengthen beam. Besides that, it was found that increased of 18.75 % of the existing load carrying capacity when the CFRP bonded with epoxy is bolted both side to the reinforced concrete beam compared to the control beam. However, there was only an increment of 12.5 % when the CFRP bonded with epoxy is bolted with rivets throughout the span with spacing at 200 mm to the reinforced concrete beam compared to the control beam. This is due to the excessive drilling bolts that has jeopardised strength of the beam itself and unlock the deterioration mechanism shortly. The same increment of 12.5 % also detected for condition where the CFRP laminate is just attaching to the beam by using epoxy only. The sample is in brittle mode and achieved failure after peeling and debonding process begin promptly at the end of the beam and spread to the whole beam structure.

While Eshwar, N, Ibell, T, & Nanni, A (2003) stated that method of applying end anchorage in the form of anchor spikes able to reduce stress concentration which consequence detachment of the CFRP strip when it faced brittle failure and enhance its bond strength.

Nevertheless, Habibur Rahman Sobuz et al. (2011) claimed that this end anchored strengthened beam display more displacement and ductility compared to those without anchored one. However, this characteristics does not show significantly in U-shaped edge strip beam. They also found that increased in the laminate layer has increased the ultimate load by 54 % for one layer of CFRP, 73 %, 85 % for two and three layer of CFRP laminate and attaching CFRP layers to both the tension part and transverse edge helps in increasing the load carrying capacity up to 82 % of the existing reinforced concrete beam.

Table 2.2: Performance of CFRP

Beam Designation	**Ultimate Load (kN)**	**Ductility Index**
Control Beam	40.3	3.81
Strengthened with 1 layer of CFRP	62.0	1.65
Strengthened with 2 layer of CFRP	69.75	1.48
Strengthened with 3 layer of CFRP	74.4	1.29
U-shape strip beam	75.95	2.28

Sources: Habibur Rahman Sobuz et al. (2011)

Table 2.3: Typical properties of carbon fibre

Typical Properties	Density (g/cm^3)	Tensile Elongation (%)	Tensile Strength (GPa)	Young Modulus (GPa)
High strength	1.8	1.1	2.48	230
High modulus	1.9	0.5	1.79	370
Ultra-High modulus	2.0-2.1	0.2	1.03-1.31	520-620

Sources: Nishikant Dash (2009)

Furthermore, geopolymer with greater adhesion, inert to external environment, fire-resistant and sturdy has been suggested to substitute the organic adhesive agent to reduce the occurrence of delamination of carbon fibre that reduces the load carrying capacity of the strengthened reinforced concrete beam (P. Balaguru, S. Kurtz, & Jon Rudolph, 1997). They have experimented for varies thickness involving two, three and five layers of the carbon fabric laminate adhere to the concrete beam by applying geopolymite resin. They have found that increased of laminate layer increases the load carrying capacity of the reinforced concrete beam without the occurrence of delamination of carbon fibre.

Table 2.4: Performance of CFRP with geopolymer resin

Beam	Load at Yielding of Steel, k	Failure Load, k	Deflection at Failure, in	Mode of Failure
Control Beam	12.5	16.0	3.5	Yielding of steel
Beam (2 layer of CFRP)	14.0	18.1	0.76	Rupture of composite
Beam (3 layer of CFRP)	15.8	20.5	0.90	Rupture of composite
Beam (5 layer of CFRP)	16.5	24.7	0.92	Rupture of composite

Source: (P. Balaguru et al., 1997)

Subedi & Baglin (1998) have claimed that steel plate is suitable to be served as external plate strengthening material in rehabilitation of reinforced concrete beam. They have found that attaching of two layer of 2 mm plate to the reinforced concrete beam has increased its serviceability by 50 % and 161 % for two layer of 6mm plate. These results can concluded that thickness of the plate will greatly enhance the flexural capacity of the reinforced concrete beam. While Siu, Wing-ho (2009) have claimed that bolted side steel plate (BSP) can used to enhance the flexural capacity of the reinforced concrete beam. Although the properties of 75 mm and 150 mm steel plate does not have significant different, however the formation of strong bolt with strong plate has increased approximately 59 % and 43 % for weak plate with strong bolt. This clearly showed that thickness of laminate will greatly influence the structural capacity of the reinforced concrete beam.

Table 2.5: Mechanical properties of the strengthening steel plate

	75 mm Plate		**150 mm Plate**	
Properties	**Young's Modulus (GPa)**	**Yield Strength (MPa)**	**Young's Modulus (GPa)**	**Yield Strength (MPa)**
Average	203	338	212	335

Sources: Siu, Wing-ho (2009)

Nishikant Dash (2009) suggested Glass Fibre Reinforced Plate (GFRP) to reinforce the reinforced concrete member. He claimed that the use of GFRP has detained the formation of cracks compared to control beam. Due to high ductility behaviour of GFRP enables users to get alert to the case of ultimate failure. The ultimate load bearing capacity of the GFRP beam are also increases about 33 % more than the control beam.

D. Goldar et al., (2005) also suggested that bolting of the GFRP and steel to the tension part can increase the structural capacity of the reinforced concrete beam. The result obtained for flexural strength for steel plate is higher than GFRP where steel plate can sustain 132 % and 129 % load for GFRP compared to the control beam. Besides that, the steel plate are able to withstand higher ultimate moment than GFRP where their differences are 0.65 kNm. Steel plate are showing better controlling of deflection and cracking of the beam when comparing to the method of implementing the GFRP.

Aluminium Glass Fibre Composite (AGC) is one of the suitable externally strengthening method to reinforce the partially-failed reinforced concrete beam (Hong, Cho, Lee, & Park, 2014). It is composed of hollow aluminium and glass fibre layers. This method is suggested to replace steel plate due to its high weight to strength ratio and convenient to handle in construction industry. They found that the cracks begin from the end edge of fibre glass and continue with failure of the aluminium inside the reinforced concrete beam. A rise of 31% to 54% of serviceability is detected from strengthened beam and downsizing of 45% for deflection when they are compared to the unstrengthen beam.

Table 2.6: Properties of materials used in AGC

Type of Materials	**Tensile Strength (MPa)**	**Modulus of Elasticity (GPa)**	**Ultimate Strain**
Aluminium Alloy 6063 T6	275	71.5	0.053
Glass Fibre W40-F60	246	14.7	0.017
Glass Fibre W80-F20	496	31.0	0.016

Sources: (Hong et al., 2014)

Aramid fibre reinforced polymer (AFRP) is one of the suitable fibre reinforced composite to advocate the structural capacity of the reinforced concrete beam (Rameshkumar U More & D. B. Kulkarni, 2014). Aramid fibre is also recognised as Kevlar fibre which commonly used in bullet and fire-resistant clothing. It has properties of high tensile strength, high modulus of elasticity, high fracture toughness, light weight and low deflection. It was found that implementing of one layer of AFRP has rose 27.59% and 48.27% for double layer compared to the unstrengthen beam. Deflection when it achieved ultimate load are also decrease when AFRP is attached to it. This result clearly displayed that the thickness of the laminate greatly influence on the structural capacity of the reinforced concrete member.

Table 2.7: Properties of ARFP

Properties	**Value**
Tensile strength (MPa)	3039
Modulus of elasticity (GPa)	127
Weight of the sheet/m^2 (gsm)	300
Density (g/cm^3)	1450
Dry fabric thickness (mm)	0.4

Sources: Rameshkumar U More & D. B. Kulkarni (2014)

2.7 CONCLUSION

This chapter has discussed the previous study related to this study regarding on introduction, characteristics of reinforced concrete, its application, deterioration, partially-failed characteristics and method of resolving the issue: demolition and rehabilitation, rehabilitation method applied to old or heritage buildings and overload buildings. Besides that, characteristics of aluminium plate and research on rehabilitation of partially-failed reinforced concrete beam are also discussed in detail in this chapter. The principal objectives in this chapter has been achieved and next chapter will converse about the methodology related to achieve the objectives of this research.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This chapter discussed on research methodology of the study and explain in advance for the test specimen design, test setup and test procedure of the study which included slump test, tensile test for aluminium coil, compressive strength and flexural strength test are carry out later. It also provides explanation of the statistical procedures used to analyze the data. Besides that, it also includes the flow chart which clearly displays how we have planned for the following steps to achieve the principal objectives of the study.

3.2 EXPERIMENTAL PROGRAMME

All beam samples was measured 150 mm wide by 200 mm deep by 1500 mm long with concrete grade 30 N/mm^2. The top, bottom and side concrete cover was 20 mm. The both top and bottom reinforcements consisted of two 12mm bars and the shear reinforcement consisted of stirrups made using 6 mm smooth bars spaced every 200 mm with standard 90° hooks.

All beam samples have undergone both compacting and curing process. Firstly, amount of evenly-mixed concrete with approximately one-third of the height of mould was poured into the mould and undergoing compaction process by using vibration table to remove air void present between concrete particles. Then, concrete was finally filled up and left for hardening process for 24 hours. Next, continue with curing process which soaked concrete samples under moisture condition for 7 and 28 days after de-moulding process has been took place.

The unstrengthen beam, C1 served as the controller for the experiment. For other three beam samples, B1, B2 and B3, they was exerted with loading until first cracks was seen, then aluminium coil with varies thickness: 0.6 mm, 1.2 mm and 1.8 mm was attached to the soffit of the partially-failed beam by bolting in order to determine the suitability of aluminium coil as external plate reinforcement, investigate the flexural behaviour and compare the structural capability between partially failed RC beam strengthen with aluminium coil and conventional RC beam (control RC beam). Then, outcomes such as ultimate flexural strength and load pattern were recorded and analyzed.

Test sample design

Table 3.1: Summary of test samples

Nomenclature	Specimen Description	Number of Bolts
C1	Control beam	-
B1	Beam strengthened with 0.6 mm thickness of aluminium coil	16
B2	Beam strengthened with 1.2 mm thickness of aluminium coil	16
B3	Beam strengthened with 1.8 mm thickness of aluminium coil	16

Figure 3.1: Arrangement of bolts on the soffit of the beam

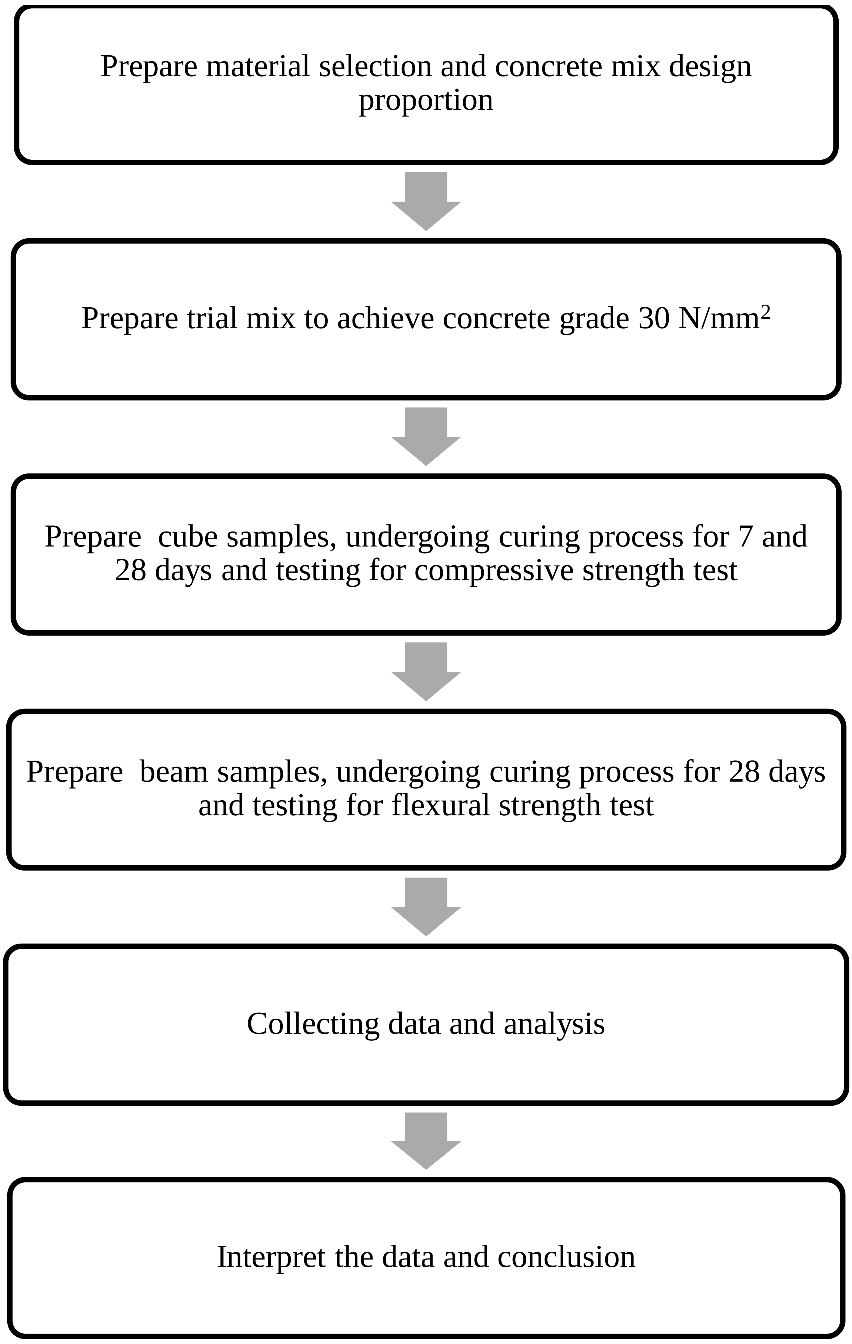


Figure 3.2: Research flow chart

3.3 TESTING

3.3.1 Tensile Test for Aluminium Coil

Tensile test was conducted in order to determine the mechanical properties such as ultimate strength, yield strength, percentage of elongation, percentage of area of reduction and Young's modulus of the aluminium coil specimen by using INSTRON Universal Testing Machine. These parameters was crucial in determining how does aluminium specimen contributes to the strengthening of the partially-failed reinforced concrete beam in construction field.

A standard specimen with thickness of 0.6 mm was prepared according to the section shown in Figure 3. Both ends of the sample was gripped firmly and load was applied to it. The test was conducted at a rate of 1.0 mm/min until a total fracture occurs.

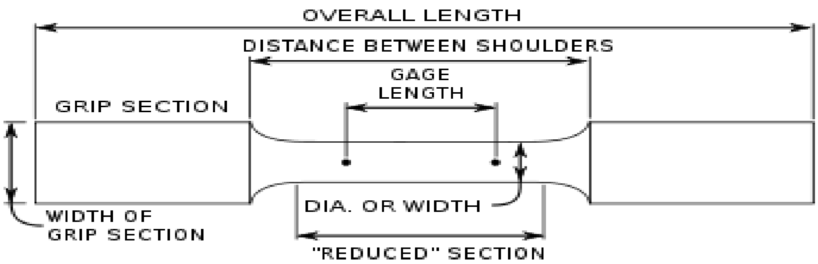


Figure 3.3: Standard sheet specimen

Calculation of mechanical properties are shown as below:

$$\text{Stress}, \sigma = \frac{P}{A_0} \tag{3.1}$$

$$\text{Strain}, \epsilon = \frac{\Delta L}{L_0} \tag{3.2}$$

$$\text{Yield strength} = \frac{\text{load at 0.2\% strain}}{A_0} \tag{3.3}$$

$$\text{Percentage of elongation} = \frac{\Delta L}{L_0} \times 100 \tag{3.4}$$

$$\text{Young Modulus, E} = \text{slope}\,\frac{\text{stress}}{\text{strain}} \tag{3.5}$$

Figure 3.4: INSTRON Universal Testing Machine

3.3.2 Concrete Compressive Test

Concrete compressive test (BS1881: Part 1 16:1983 and ASTM C39-03) was carried out to ensure the consistency of the compressive strength of the concrete grade 30 N/mm^2 at 7 and 28 days. The concrete cubes' ages with 7 and 28 days with size of 150 mm x 150 mm x 150 mm are tested until it reached failure and the maximum load achieved was considered as the ultimate load for future strength calculation.

Calculation of error, E and percentage of error, E_p are shown as below:

$$E = A - B \tag{3.6}$$

$$E_p = 100(A-B)/B \tag{3.7}$$

A = load, lbf (kN) indicated by the machine being verified

B = applied load, lbf (kN) as determined by the calibrating device

$$\text{Compressive Strength,} F_c = \frac{Maximum\ Load(N)}{Surface\ Area(mm^2)} \tag{3.8}$$

Figure 3.5: Concrete compression test

3.3.3 Concrete Flexural / Re-strengthening Test

Re-strengthening test is carried out to determine whether the application of attachment of aluminium laminate to the beam's soffit will deflect its' effect to the deflection and ultimate strength of partially-failed beam samples under four point loading. A total of four samples with size 150 mm x 200 mm x 1500 mm with concrete achieving 30 N/mm^2 at 28 days will be tested.

The control beam will be exerted loading until first crack has appeared and continuous loading has applied until it has reached total failure. While for other beam samples, loadings will be applied to them until first crack has observed. Then, beams will be removed and a layer of 0.6 mm, 1.2 mm and 1.8 mm of aluminium coil will be bolting to the beneath of the partially- failed beams. Continuous loading will be applied to them until they have reached total failure.

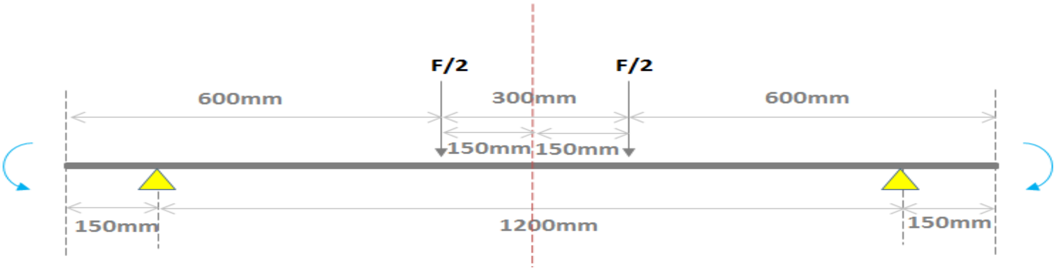
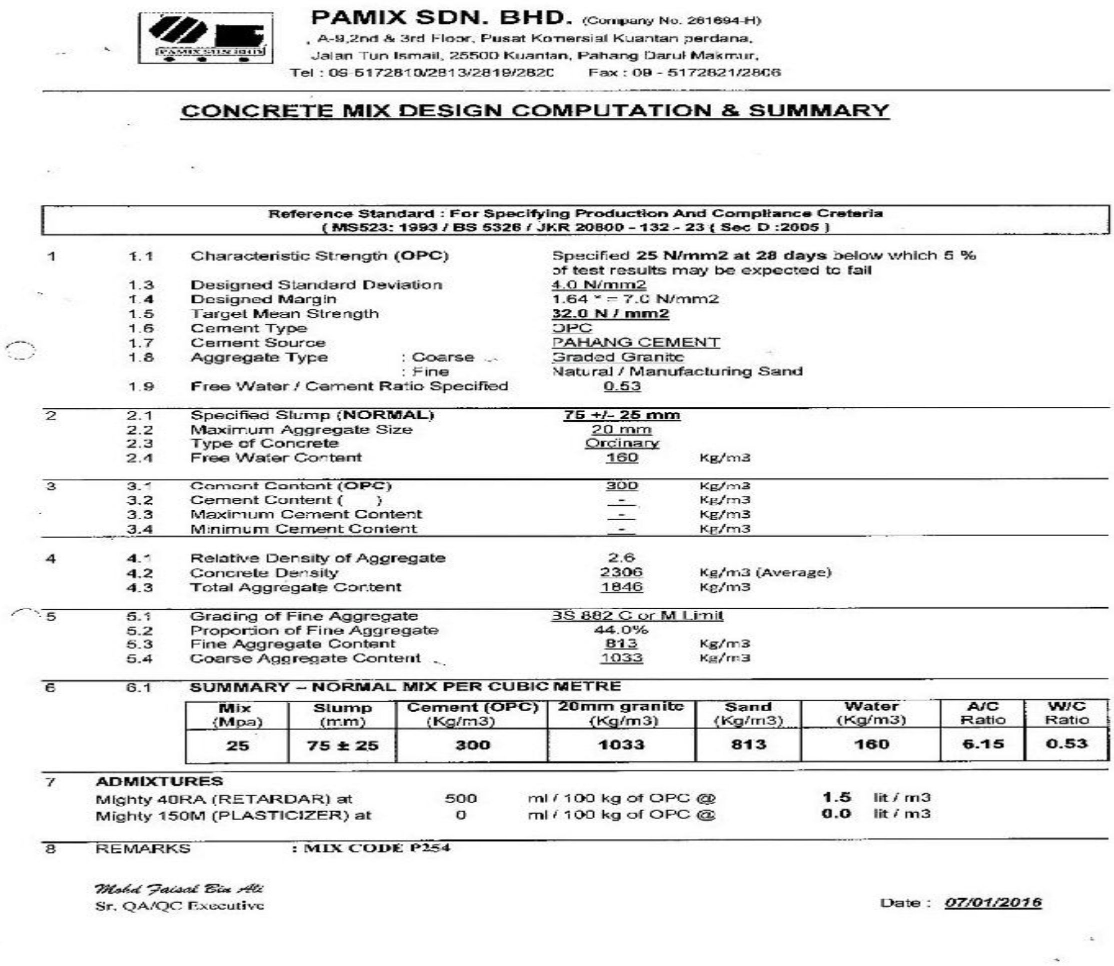


Figure 3.6: Schematic of a suitable apparatus for flexure test of concrete by four-point loading method

3.4 CONCRETE MIX DESIGN (PROVIDED BY PAMIX SDN. BHD.)

Target mean strength of concrete designed for this study was estimated to be 32.0 N/mm^2 at 28 days and free water cement ratio of 0.53.



PAMIX SDN. BHD. (Company No. 281694-H)
, A-9,2nd & 3rd Floor, Pusat Komersial Kuantan perdana,
Jalan Tun Ismail, 25500 Kuantan, Pahang Darul Makmur,
Tel : 09-5172810/2813/2819/2820 Fax : 09 - 5172821/2806

CONCRETE MIX DESIGN COMPUTATION & SUMMARY

Reference Standard : For Specifying Production And Compliance Creteria
(MS523: 1993 / BS 5326 / JKR 20800 - 132 - 23 (Sec D :2005)

1	1.1	Characteristic Strength (OPC)	Specified **25 N/mm2 at 28 days** below which 5 % of test results may be expected to fail	
	1.3	Designed Standard Deviation	4.0 N/mm2	
	1.4	Designed Margin	1.64 * = 7.0 N/mm2	
	1.5	Target Mean Strength	**32.0 N / mm2**	
	1.6	Cement Type	OPC	
	1.7	Cement Source	PAHANG CEMENT	
	1.8	Aggregate Type : Coarse	Graded Granite	
		: Fine	Natural / Manufacturing Sand	
	1.9	Free Water / Cement Ratio Specified	0.53	
2	2.1	Specified Slump (NORMAL)	**75 +/- 25 mm**	
	2.2	Maximum Aggregate Size	20 mm	
	2.3	Type of Concrete	Ordinary	
	2.4	Free Water Content	160	Kg/m3
3	3.1	Cement Content (OPC)	300	Kg/m3
	3.2	Cement Content ( )	-	Kg/m3
	3.3	Maximum Cement Content	-	Kg/m3
	3.4	Minimum Cement Content	-	Kg/m3
4	4.1	Relative Density of Aggregate	2.6	
	4.2	Concrete Density	2306	Kg/m3 (Average)
	4.3	Total Aggregate Content	1846	Kg/m3
5	5.1	Grading of Fine Aggregate	BS 882 C or M Limit	
	5.2	Proportion of Fine Aggregate	44.0%	
	5.3	Fine Aggregate Content	813	Kg/m3
	5.4	Coarse Aggregate Content	1033	Kg/m3

6 6.1 **SUMMARY – NORMAL MIX PER CUBIC METRE**

Mix (Mpa)	Slump (mm)	Cement (OPC) (Kg/m3)	20mm granite (Kg/m3)	Sand (Kg/m3)	Water (Kg/m3)	A/C Ratio	W/C Ratio
25	75 ± 25	300	1033	813	160	6.15	0.53

7 **ADMIXTURES**

Mighty 40RA (RETARDAR) at	500	ml / 100 kg of OPC @	**1.5**	lit / m3
Mighty 150M (PLASTICIZER) at	0	ml / 100 kg of OPC @	**0.0**	lit / m3

8 REMARKS : MIX CODE P254

Mohd Faisal Bin Ali
Sr. QA/QC Executive

Date : *07/01/2016*

Figure 3.7: Concrete Mix Design

3.5 CONCLUSION

This chapter has outlined the introduction, experimental programme, test setup and test procedure for compressive and flexural strength test. The main objectives of the study has been finalised and the next chapter will discuss on results and discussions on the data collected from the samples.

CHAPTER 4

RESULT AND ANALYSIS

4.1 INTRODUCTION

In this chapter, results obtained from the experimental procedure and associated data analysis was discussed in advance to determine the suitability of aluminium coil as external plate reinforcement for partially-failed reinforced concrete beam with grade C30. The data obtained mainly focused on the mechanical properties of the aluminium coil itself and flexural strength of the reinforced concrete beam. Besides that, deflection, first crack and crack pattern of each samples were recorded with aims to achieve objectives of the study. These data was illustrated in table and graph form to provide a clearer platform for us to observe and compare the result of the strengthening beam and the control beam. It helps in determining whether our objectives of the study are achieved or not clearly.

4.2 COMPRESSION TEST ON CUBE SAMPLES

Concrete compressive test on cube samples (BS1881: Part 1 16:1983 and ASTM C39-03) are carried out to ensure the consistency of the compressive strength of the concrete grade 30 N/mm^2 at 7 and 28 days. The average compressive strength for concrete cubes' ages with 7 and 28 days with size of 150 mm x 150 mm x 150 mm are 24.045 MPa and 31.735 MPa which comply with the design of grade of C30 for the concrete.

Table 4.1: Result of curing cubes' compressive strength for 7 and 28 days

Sample	Weight (kg)	Sample Age (days)	Load (kN)	Compressive Strength (MPa)	Average Compressive Strength (MPa)
1	7.55	7	506.984	22.533	
2	7.70	7	513.572	22.825	
3	7.85	7	524.877	23.328	24.045
4	7.85	7	552.675	24.563	
5	7.85	7	606.993	26.977	
6	7.70	28	722.284	32.102	
7	7.75	28	694.799	30.879	
8	7.75	28	748.625	33.272	31.735
9	7.61	28	705.268	31.345	
10	7.73	28	699.207	31.076	

4.3 TENSILE TEST FOR ALUMINIUM COIL

Tensile test for aluminium coil has been performed in order to determine its mechanical properties such as ultimate strength, yield strength, percentage of elongation and Young's modulus.

Figure 4.1: Tensile test of aluminium coil

Stress-strain curve was drawn in order to give a clearer image for the calculation of the mechanical properties of aluminium coil. Stress is equal to load over original cross sectional area and strain is increase in length under load over original length.

$$\text{Yield strength} = \frac{\text{load at } 0.2\% \text{ strain}}{A_0} = 48.31 \text{ MPa} \tag{4.1}$$

$$Percentage \text{ of elongation} = \frac{10.5-10.4}{10.4} \text{x } 100 = 0.96\% \tag{4.2}$$

$$E = \frac{38.022056-20.095295}{0.001997-0.000703} = 13.85 \text{ GPa} \tag{4.3}$$

From stress-strain curve where it was plotted according to the experimental data, ultimate tensile strength was 50.25 MPa and maximum load that it sustained was 363.302 N. As aluminium metal has a FCC crystal structure where definite yield point is absent, therefore its yield strength has to be calculated according to the formulae load at 0.2 % strain over initial cross sectional area (Shackelford, 2005). Thus, the yield strength obtained was 48.31 MPa. The percentage of elongation of the aluminium coil was 0.96 % and young modulus 13.85 GPa.

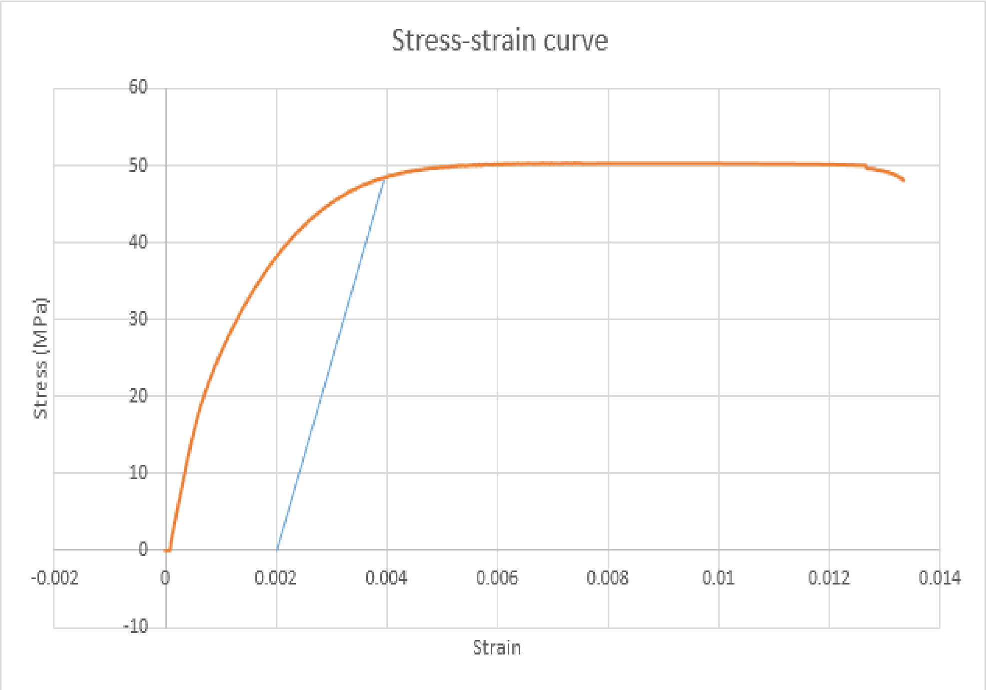


Figure 4.2: Stress-strain curve

4.4 LOAD THEORY (BASED ON EUROCODE 2)

The achievement of reinforced concrete beam when load was exerted to it is greatly influenced by stress-strain relationship between concrete and reinforcing steel and types of stress that the material is subjected to. The figure 6 above illustrates the cross-section stress and strain distributions at ultimate limit state of a singly reinforced beam section. It was very crucial for us to foreseen the ultimate strength and ultimate moment resistance of the beam.

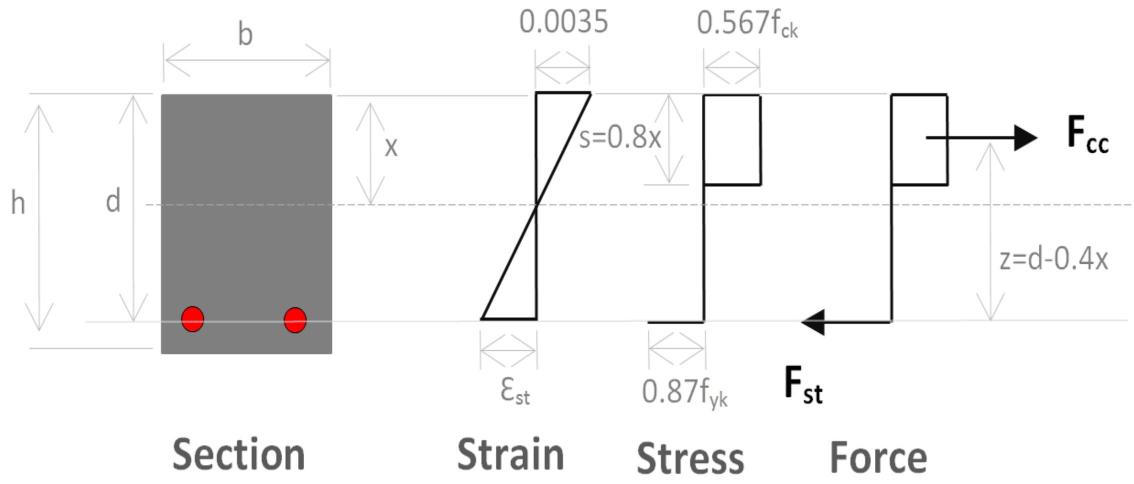


Figure 4.3: Singly reinforced section with rectangular stress block

By referring to the stress-strain distribution, the upper part are dealing with compressive stress and the lower part was dealing with tensile stress. Neutral axis of the member was observed in between the upper and lower part where the bending stress are at zero. This information was important in designing balanced section with balanced steel ratio which indicates the right amount of reinforcing bar induces beam to fail by crushing of concrete and steel to yield simultaneously when the same load applied to it.

4.4.1 Specification

The reinforced concrete beam samples was designed according to the specification as shown as below. These specification helps in determining the theoretical ultimate strength and moment of the beam accurately.

Dimension:

Length of beam, L	=	1500 mm
Size, b x d	=	150 mm x 200 mm

Materials:

Concrete strength, f_{cu}	=	30 N/mm^2
Shear link strength, f_{yv}	=	250 N/mm^2
Reinforcement strength, f_{yk}	=	460 N/mm^2
Nominal concrete cover, C	=	20 mm
Diameter of reinforcement of main bar, $\varnothing_{Bar}$	=	12 mm
Diameter of reinforcement of shear link, $\varnothing_{Link}$	=	6 mm

4.4.2 Design Analysis

Effective depth

$$d = h - c - (bar/2) - link \tag{4.5}$$

$$= 200 - 20 - (12/2) - 6$$

$$= 168 \text{ mm}$$

Forces

$$F_{cc} = 0.454\ f_{ck}\ b\ \varkappa \tag{4.6}$$

$$= 0.454\ (30)\ (150)\ (\varkappa)$$

$$= 2043\varkappa\ \text{N}$$

$$F_{st} = 0.87\ f_{yk}\ A_s \tag{4.7}$$

$$= 0.87 \text{ x } 460 \text{ x } 226$$

$$= 90445.2\ \text{N}$$

Equilibrium of forces

$$F_{cc} = F_{st}$$

$$2043\varkappa = 90445.2$$

$$K = 44.27\ \text{mm}$$

Lever arm

$$z = d - 0.4\ \varkappa \tag{4.8}$$

$$= 168 - 0.4\ (44.27)$$

$$= 150.29\ \text{mm}$$

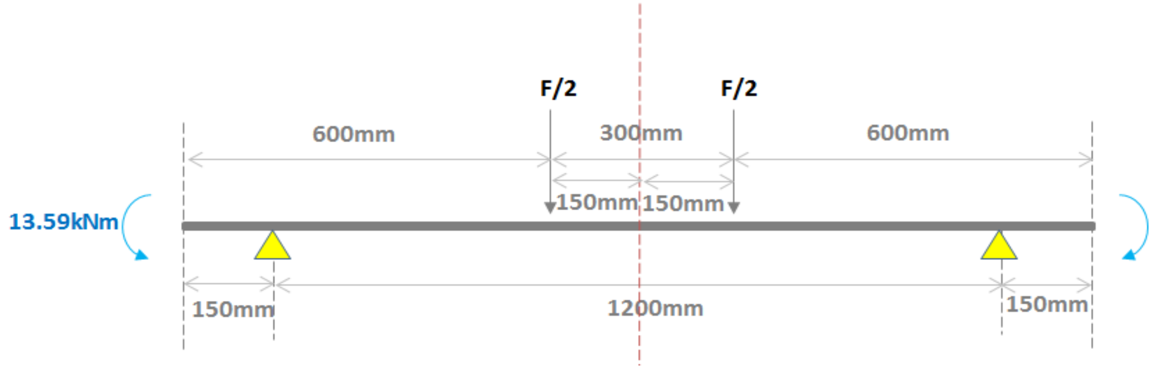
Moment of resistance

$$M = F_{st}\ z \tag{4.9}$$

$$= 0.87\ f_{yk}\ A_s\ z$$

$$= 0.87 \text{ x } 460 \text{ x } 226 \text{ x } 150.29 \text{ x } 10^{-6}$$

$$= 13.59\ \text{kNm}$$



Let Maximum load, P = F/2

Consider only half part of the beam, taking moment at end of the beam,

P(0.6) - P(0.15) - 13.59 = 0

F = 60.40 kN

4.5 RESTRENGTHENING TEST OF THE BEAM SAMPLES

Re-strengthening test was performed on several reinforced concrete beams where their concrete' age have reached its maturity at 28 days. Flexural strength and first crack of each samples were recorded. Then, the experimental procedure was followed by re-strengthening test for sample B1 which strengthened by bolting a layer of 0.6 mm of aluminium coil, B2 with 1.2 mm aluminium coil and B3 with 1.8 mm aluminium coil. The experimental results were then jot down with aims to achieve objectives of the study. These data were illustrated in table and graph form which enables a clearer observation and comparison between beam samples to be carried out.

Table 4.2: First crack, ultimate load and ultimate load comply with serviceability limit state

Samples	First Crack Load (kN)	Ultimate Load (kN)	Ultimate Load comply with serviceability limit state (kN)
C1	27.83	63.49	63.49
B1	22.75	71.88	70.50
B2	19.75	78.07	78.07
B3	18.89	96.21	89.58
Theoretical	-	60.40	-

In this study, ultimate load of the control beam was recorded and compared with the strengthened reinforced concrete beams. It was observed that the ultimate load in the experimental result was slightly higher than the theoretical result which was 5.12% or 3.09 kN. According to Shanmugam, Liew, Thevendran (1998), the ultimate load prediction underrates by 1.91% to 19.11% when they was calculated by referencing the design procedure will be provided a more conservative estimation. It leads to an adequate reinforced concrete beam design. Sample B1 was increased its ultimate load estimated up to 13.21% compared to the control beam. Sample B2 was gained 22.96% more flexural strength and B3 was boost up to 51.54% compared to the control beam. The results clearly proved that increases of the thickness of the aluminium laminate was greatly increased the ultimate load of the reinforced concrete beam.

Furthermore, first crack load of reinforced concrete beams were traced and compared between each other. It was observed that Sample C1 was having the highest first crack load, 27.83 kN and followed by sample B1, 22.75 kN where it reduced by 5.08 mm or 18.25%. Then, it continued by sample B2 with 19.75 kN and B3 with 18.89 kN where it dropped by 8.08 mm or 29.03% and 8.94 mm or 32.12% respectively.

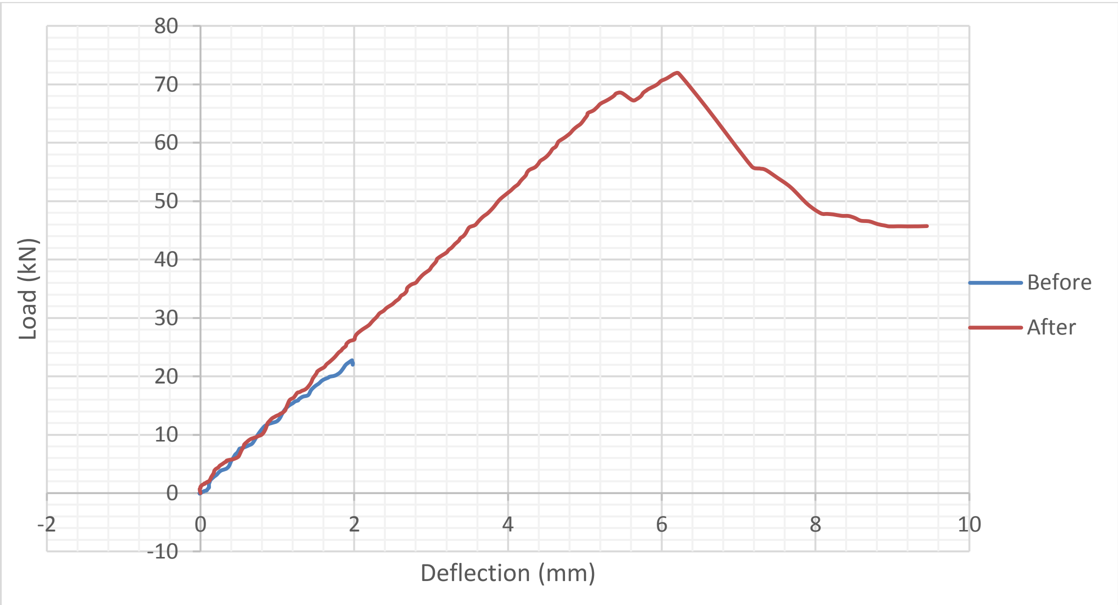


Figure 4.4: Load deflection curve for sample B1

Figure 4.4 was plotted according to the experimental data that obtained in appendix A2 and A3 clearly portrayed the comparison of load-deflection results for sample B1 between before and after strengthening by bolting a layer of 0.6 mm thick aluminium coil to the beam's soffit. It was observed that the trend line for both load-deflection curve was almost the same in the beginning until the load was increased till it reached 15.11 kN. Then, it can be observed that the deflection for after strengthening result is slightly less than the before strengthening as load imposed to the beam increased. It was clearly showed that the imposed load for the after strengthening was increased by 18.85% compared to the before one for the similar deflection value. This greatly proved that addition of 0.6 mm aluminium laminate to the soffit of the beam was reduced the deflection of the beam as imposed load increased.

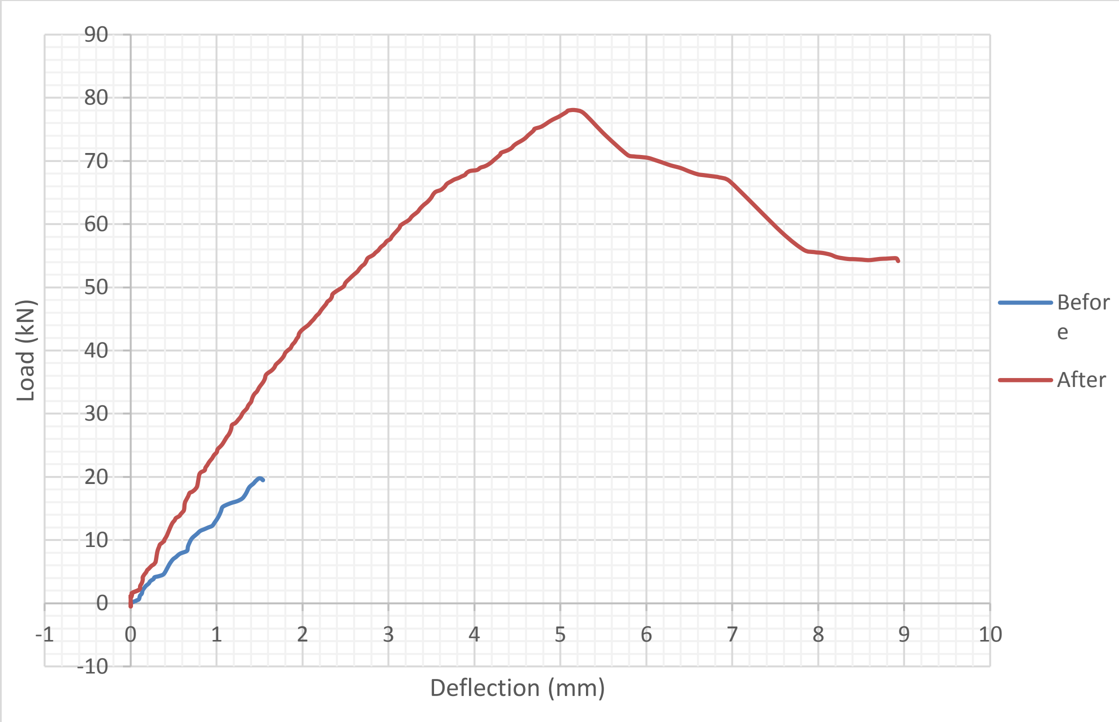


Figure 4.5: Load deflection curve for sample B2

Figure 4.5 was drawn according to the experimental data that obtained in appendix A4 and A5 clearly showed the comparison of load-deflection results for sample B2 for before and after retrofitting by bolting a layer of 1.2 mm thick aluminium coil to the beam's soffit. It was observed that the trend line for after strengthening result was lesser compared to the result for before strengthening as load imposed to the beam increased. It was clearly observed that the imposed load for the after strengthening was increased by 79.11% compared to the before one for the same deflection value. This greatly proved that attachment of a layer of 1.2 mm aluminium laminate to the beneath of the beam was greatly lowered down the deflection of the beam as imposed load increased.

Figure 4.6: Load deflection curve for sample B3

Figure 4.6 was drawn according to the experimental data that obtained in appendix A6 and A7 presented the comparison of load-deflection results for sample B3 for before and after enhancement of flexural capacity by bolting a layer of 1.8 mm thick aluminium coil to the beam's soffit. It was observed that the trend line for both load-deflection curves was almost the same in the beginning until the load was boost up until it reached 9.55 kN. Then, it was noticed that the deflection for after strengthening result is a bit less than the before strengthening as load imposed to the beam increased. It was clearly showed that the imposed load for the after strengthening was increased by 50.52% compared to the before one for the similar deflection value. This greatly proved that bolting of 1.8 mm aluminium coil to the soffit of the beam was reduced the deflection of the beam as imposed load increased.

4.6 DEFLECTION THEORY (BASED ON ACI 318)

Deflection is the amount of displacement of a structural element when load is exerted on it. It is influenced by slope of the deflected shape of the structural member under load and can be calculated by several methods such as Macaulay's method and virtual method.

Over-deflection would not lead to the total failure of a beam structure. However, it is crucial for us to ensure that extreme deflection of the beam structure due to unfactored imposed loading is not going to happen in the future in order to avoid total failure such as damage to various architectural features, ceilings, glass façade and other fragile non-structural elements and forming severe cracking in brittle finishes. In this study, the deflections measured at the center of the beam by using displacement transducers.

$$n = \frac{E_{steel}}{E_{concrete}} \quad (4.10)$$

$$= \frac{200}{17}$$

$$= 11.76$$

$$0 = \frac{b}{2}c^2 + 226nc - 226nd \quad (4.11)$$

$$0 = \frac{150}{2}c^2 + 226(11.76)c - 226(11.76)d$$

$$0 = 75c^2 + 2657.76c - 446503.68$$

$$c = 61.45$$

Moment of inertia

$$I_{cr} = \frac{bc^3}{3} + [(d-c)^2 (n \times A_s)] \tag{4.12}$$

$$= \frac{(150)(61.45)^3}{3} + [(168 - 61.45)^2 (11.76 \times 226)]$$

$$= 0.42 \times 10^8 \text{ mm}^4$$

For P = 5 kN, E = 200 GPa & $I_{cr} = 0.42 \times 10^8$ mm^4

$$\Delta max = \frac{PL^3}{48\,EI}\left[\left[\frac{3a}{L} - 4\left(\frac{a}{L}\right)^3\right] + \left[\frac{3b}{L} - 4\left(\frac{b}{L}\right)^3\right]\right] \tag{4.13}$$

$$= \frac{5 \times 10^3 \times 1200^3}{48 \times 200 \times 10^3 \times 0.42 \times 10^8}\left[\left[\frac{3(450)}{1200} - 4\left(\frac{450}{1200}\right)^3\right] + \left[\frac{3(750)}{1200} - 4\left(\frac{750}{1200}\right)^3\right]\right]$$

$$= 0.0388 \text{ mm}$$

In this study, the moment of inertia used was $I_{cr} = 0.42 \times 10^8$ mm^4 which assumed the worst case for the beam section where it was under condition of cracked and transformed at the moment of yielding of steel instead of using $I_g = 1.0 \times 10^8$ mm^4 which assuming the gross concrete section and reinforcements was ignored in the calculation. Modulus of elasticity, E used in this study was 200 GPa which was the modulus of elasticity of steel and 11.76 GPa which was the ratio of modulus of elasticity of steel to modulus of elasticity of concrete. These values was important to determine whether the bending behavior of beam samples was lied between these graphs.

Figure 4.7 was plotted from results in table A8 and appendix A1, A3, A5 and A7 portraying the comparison between theoretical and experimental result for beam specimens that have been re-strengthened. The experimental result for a total of four beam specimens lied between theoretical result which utilizing E = 200 GPa and 11.76 GPa with moment of inertia, I_{cr} of 0.42 x 10^8 mm^4. It was observed that the bending behavior of all beam specimens that have been re-strengthened was having similar trend line when load was imposed to them.

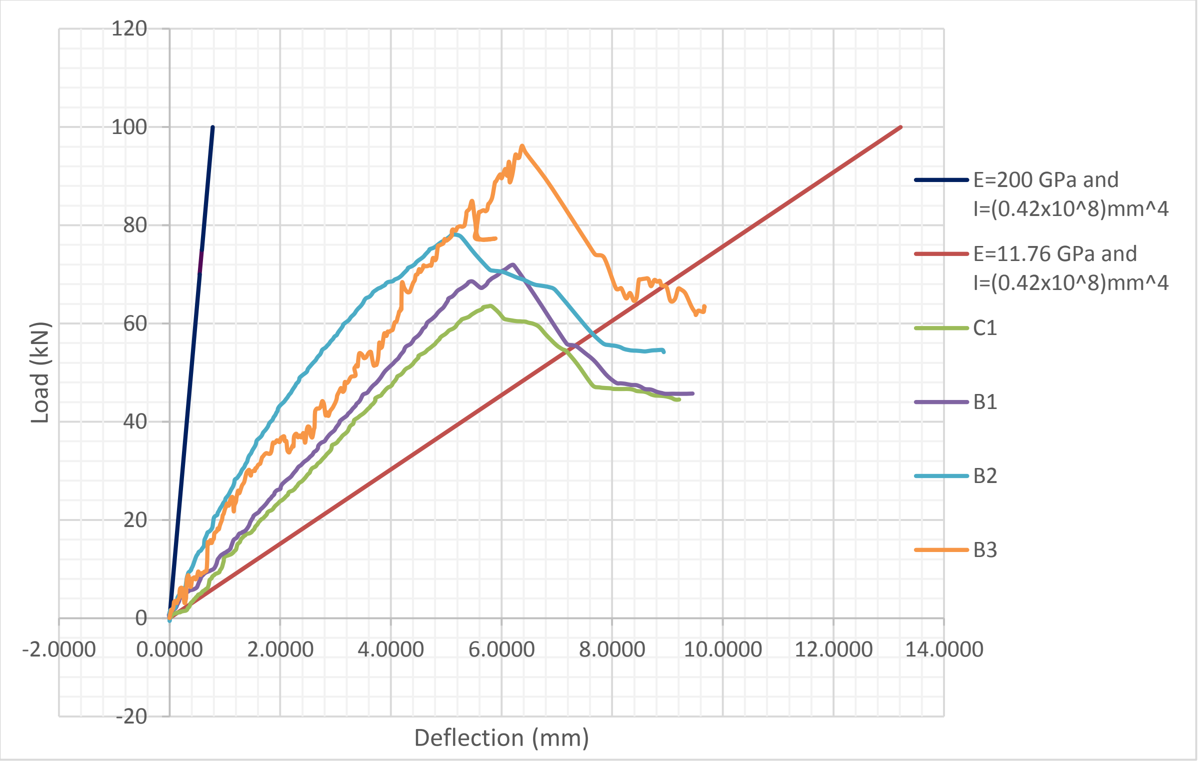


Figure 4.7: Load-Deflection curve

Besides that, sample B3 was stronger in term of ultimate strength and deflection compared to sample B2, B1 and C1. Sample B3 achieved the highest ultimate strength of 96.21 kN and deflected at 6.37 mm compared to B2 with ultimate strength of 78.07 kN and deflected at 5.17 mm. It follows by B1 with 71.88 kN and deflected at 6.22 mm, and C1 with 63.49 kN deflected at 5.82 mm. While the ultimate load comply with the serviceability limit state where maximum deflection was equal to 6 mm whereby calculated according to the formula of total beam length over 250, sample B3 was obtained the highest ultimate strength of 89.58 kN, followed by 78.07kN, 70.5 kN and 63.49 kN for sample B2, B1 and C1.

On the other hand, it was calculated that theoretical maximum load was 60.40 kN. When the loading was 60.40 kN, the deflection value for I_{cr} when E = 200 GPa was 0.47 mm and 7.93 mm when E = 11.76 GPa. It was observed that the remaining deflection value was lied between 0.47 mm and 7.93 mm. At the same loading applied, the deflection value was showed a decreasing trend from sample C1 to B2. Sample C1 had the highest deflection value in this experiment which was 5.25 mm. Its deflection value was higher than sample B1, 4.66 mm which exceeded about 0.59 mm or 11.24%. It followed by sample B2, 3.19 mm where its' deflection value had decreased by 2.06 mm or 39.24% compared to the control beam. While sample B3 was having a deflection value of 4.10 mm where its' deflection value has dropped by 1.15 mm or 21.90% compared to the control specimen. This performance demonstrates addition of aluminium coil to the beam can be served as tool that enhance the flexural strength of reinforced concrete beam.

4.7 CRACK PATTERN ON BEAMS

The crack pattern of beam specimens were observed throughout the experiment where they experienced applied loads until they reached total failure. The blue color indicates the crack found on the beam when it was exerted by loading until second crack has present before strengthening process has been carried out. The red color indicates how the crack was distributed after loading was applied to the beam where layers of aluminium coils have been bolted to the beam' soffit. The main aim to observe the first crack was to determine the location of the first crack and whether their presence influence the ultimate strength of the sample or not. The position of the first crack may not serve as telltale marker of where the sample may reach failure (Bruno Boursier & Alfonso Lopez, 2010).

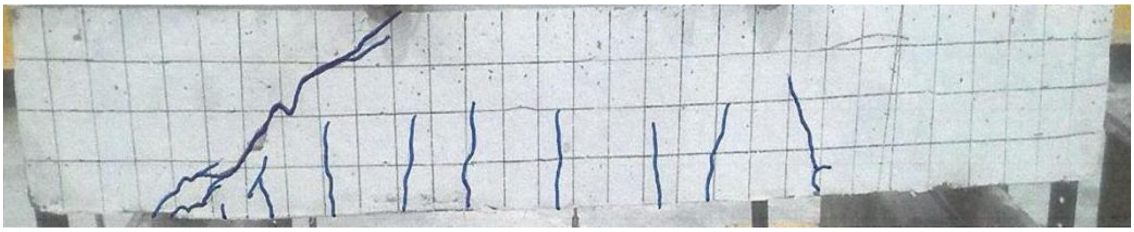


Figure 4.8: Crack pattern of control beam

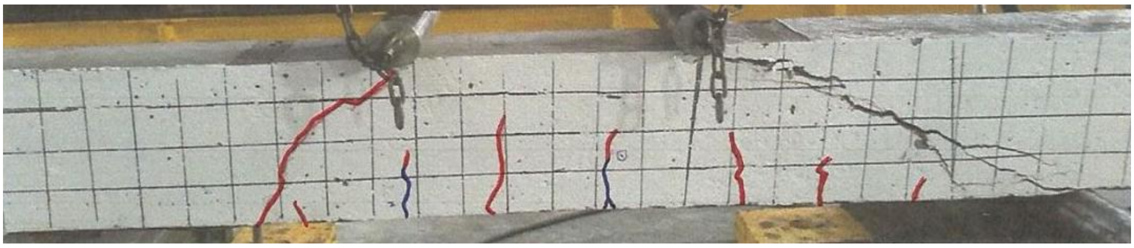


Figure 4.9: Crack pattern of B1

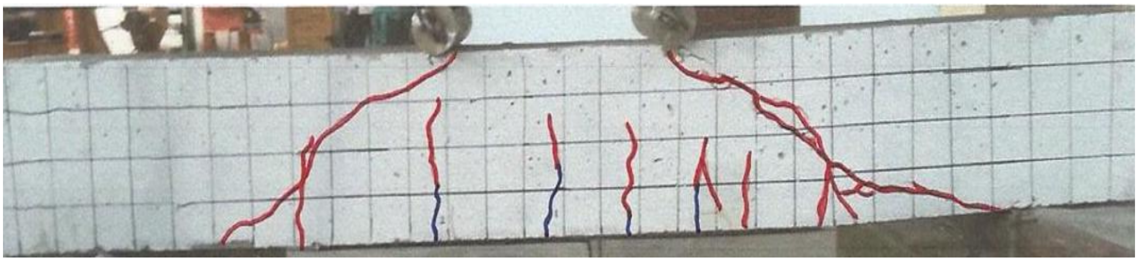


Figure 4.10: Crack pattern of B2

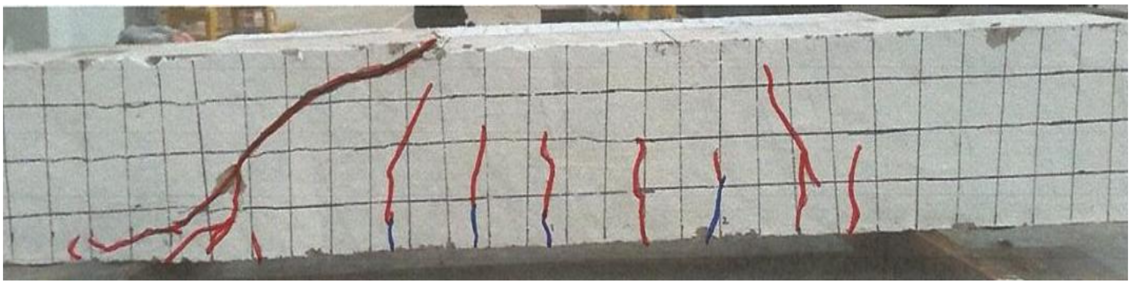


Figure 4.11: Crack pattern of B3

It was observed that all beams have failed in the same manner as shown in figure 4.8, 4.9, 4.10 and 4.11. The cracking in beam specimens starts in the tensile zone which meant the bottom part of the beam where they was marked by using blue marker pen on the reinforced concrete beam. It mainly propagated at the mid span of the beam in vertical direction towards the location of loading. These vertical pattern of cracks clearly illustrate the type of cracks, flexural crack when load is applied to it. Then, cracks were continuously distributed from the initial crack detected at the beam’ soffit to the top of beam when increasing load. Lastly, the beam reached total failure when the crack pattern was started appear at the support part and distributed inclined till the top of the beam due to the combined effect of shear and flexure and splits at the end. This final crack indicates flexure-shear failure.

4.8 CONCLUSION

In conclusion, this chapter have outlined the introduction, compression test on cube samples, tensile test for aluminium coil, flexural test on beam samples, load theory and deflection theory. From the experimental analysis, it was clearly showed that the imposed load that can be sustained for the after strengthening beam was increased by 18.85%, 79.11% and 50.52% compared to the before one for the similar deflection value of sample B1, B2 and B3. It was observed that Sample B1 increased its flexural strength up to 13.21%, Sample B2, 22.96% and B3 with 51.54% compared to the control beam. The next chapter will discuss on conclusion and recommendation of the study in order to improve the study to a higher level.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 INTRODUCTION

Although the design working life for the reinforced concrete structure is about 100 years, however due to several factors, they may have lost its structural performance before reaching the ultimate designed lifespan. Therefore, this research study intend to study and investigate the enhancement of the flexural performance of external strengthening method applied by bolting layers of aluminium coil to the beneath of the beam to rehabilitate the existing partially-failed reinforced concrete beams.

Besides that, this study targets to investigate the suitability of partially failed RC beam strengthening with aluminium coil on the soffit of the beam, to compare the flexural strength between partially failed RC beam strengthen with aluminium coil and conventional RC beam (control RC beam) and to determine relationship of load applied to the deflection and pattern of cracking of the reinforced concrete beam. Conclusions and recommendations regarding on any alteration of the study will be discussed then in this chapter.

5.2 CONCLUSIONS

After the material testing and experiments on beams had been performed, conclusion can be made and the main objectives of the study was to determine the suitability of aluminium coil as external plate reinforcement for partially failed RC beam is finally achieved.

The first objective was to investigate the flexural behaviour of partially failed RC beam strengthen with aluminium coil on the soffit of the beam. It can be observed that the deflection for after strengthening result of sample B1 was slightly less than the before strengthening as load imposed to the beam increased. It was clearly showed that the imposed load for the after strengthening was increased by 18.85%, 79.11% and 50.52% compared to the before one for the similar deflection value of sample B1, B2 and B3. This greatly proved that addition of a layer of aluminium laminate to the soffit of the beam was reduced the deflection of the beam as imposed load increased.

The second objective was to compare the flexural strength between partially failed RC beam strengthen with aluminium coil and conventional RC beam (control RC beam). Through several analytical and experimental investigations, it was observed that Sample B1 where 0.6 mm of aluminium coil was bolted to the beam' soffit has increased its flexural strength estimated up to 13.21% compared to the control beam. Sample B2 with 1.2 mm thickness of aluminium coil has gained 22.96% more flexural strength and B3 with 1.8 mm thickness has boost up to 51.54% compared to the control beam. These performances clearly proved that increases of the thickness of the aluminium laminate was increased the flexural strength of the reinforced concrete beam.

The third objective was to determine pattern of cracking of the reinforced concrete beam. It was observed that all beams have failed in the same manner. The cracking in beam specimens starts in the tensile zone which meant the bottom part of the beam where they was marked by using blue marker pen on the reinforced concrete beam. It mainly propagated at the mid span of the beam in vertical direction towards the location of loading. These vertical pattern of cracks clearly illustrate the type of cracks, flexural crack when load is applied to it. Then, cracks were continuously distributed from the initial crack detected at the beam' soffit to the top of beam when increasing load. Lastly, the beam reached total failure when the crack pattern was started appear at the support part and distributed inclined till the top of the beam due to the combined effect of shear and flexure and splits at the end. This final crack indicates flexure-shear failure.

Overall conclusions that can be made throughout this study was proved that the addition of aluminium laminates to the beam' soffit was an alternate solutions to replace other materials in retrofitting partially-failed reinforced concrete beam as it able to enhance the flexure behavior of the reinforced concrete beam.

5.3 RECOMMENDATIONS

There was several items to be reviewed and improved in order to produce a more reliable research study. Hence, recommendations are made to improve the result obtained in the study and analyzed for future research study. The recommendations are shown as below.

1. This study can be conducted with different beam dimension such as altering the depth or length of the total beam from 1.5 m to 2.0 m. This may help to determine in precisely regarding on the suitability of application of aluminium laminate to the beam's soffit helps in enhancing the flexural strength of the beam itself with different beam dimension.
2. This study can be experimented with applying more beam samples involved. For an instance, in this study, there was only a total of four reinforced concrete beams was casted and tested under four point loading. Consequently, there was only a single beam specimen applied under each condition where they are bolting by a layer of 0.6 mm, 1.2 mm and 1.8mm. Thus, there is lack of precise information for each condition. This recommendations may help in determine the suitability of application of aluminium laminate to the beam's soffit helps in enhancing the flexural strength of the beam itself accurately.
3. Further tests can be carried out by alteration of the beam geometry. This may help in improvement of both flexural and shear strength of beams by determining the best arrangement of where aluminium coil should attached to it.

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APPENDIX A1

LOAD-DEFLECTION DATA (BEAM C1)

Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)
0	0	1.29	0.2	8.77	0.81
0	0	1.3	0.21	8.9	0.82
-0.01	0	1.33	0.21	9.03	0.84
0.07	0.01	1.39	0.24	9.15	0.87
0.14	0.02	1.44	0.26	9.23	0.88
0.18	0.02	1.47	0.28	9.34	0.9
0.2	0.02	1.54	0.3	9.68	0.91
0.24	0.02	1.75	0.32	9.99	0.93
0.25	0.02	2.05	0.33	10.4	0.95
0.28	0.02	2.22	0.35	11.24	0.97
0.3	0.02	2.62	0.37	11.65	0.98
0.34	0.03	3	0.38	11.99	0.98
0.42	0.03	3.33	0.41	12.31	0.99
0.45	0.04	3.58	0.43	12.57	1.01
0.55	0.04	3.76	0.44	12.72	1.05
0.68	0.04	3.96	0.46	12.85	1.08
0.69	0.05	4.24	0.48	12.98	1.11
0.76	0.05	4.45	0.5	13.13	1.13
0.79	0.06	4.61	0.51	13.33	1.15
0.85	0.08	4.78	0.52	13.6	1.17
0.91	0.09	4.84	0.54	13.92	1.2
0.93	0.09	4.91	0.55	14.31	1.21
0.94	0.1	5.05	0.57	15.03	1.23
0.97	0.11	5.15	0.58	15.46	1.27
1.03	0.11	5.28	0.59	15.77	1.28
1.03	0.12	5.31	0.59	16.17	1.3
1.07	0.13	5.44	0.6	16.5	1.33
1.06	0.13	5.65	0.63	16.74	1.35
1.1	0.14	5.92	0.66	16.85	1.37
1.13	0.15	6.19	0.69	17.02	1.37
1.11	0.16	6.89	0.71	17.13	1.39
1.15	0.17	7.57	0.72	17.23	1.44
1.17	0.18	7.83	0.73	17.47	1.48
1.16	0.19	8.09	0.76	17.76	1.5
1.19	0.19	8.39	0.77	18.1	1.53
1.26	0.2	8.61	0.79	19.08	1.59

Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)
19.86	1.64	31.79	2.72	46.55	3.91
20.1	1.66	32.18	2.75	46.95	3.95
20.29	1.69	32.56	2.78	47.15	3.99
20.54	1.71	32.9	2.81	47.44	4.02
20.88	1.74	33.32	2.84	47.88	4.04
21.17	1.76	33.56	2.86	48.25	4.07
21.49	1.77	33.88	2.89	48.74	4.1
21.76	1.8	34.33	2.92	49	4.11
21.94	1.84	34.77	2.93	49.22	4.12
22.22	1.87	35.22	2.94	49.58	4.18
22.56	1.89	35.48	2.99	50.02	4.22
22.93	1.92	35.79	3.03	50.5	4.25
23.22	1.95	36.24	3.06	50.87	4.29
23.56	1.98	36.59	3.09	51.08	4.33
23.79	2	37.04	3.12	51.45	4.37
23.97	2.03	37.35	3.15	51.77	4.4
24.24	2.06	37.6	3.18	52.11	4.42
24.59	2.09	38.06	3.22	52.48	4.45
24.83	2.11	38.53	3.24	52.81	4.48
25.14	2.14	39.01	3.26	53.07	4.5
25.5	2.15	39.32	3.29	53.4	4.5
25.72	2.17	39.56	3.32	53.82	4.57
25.93	2.22	40	3.33	54.12	4.62
26.28	2.26	40.35	3.34	54.59	4.66
26.6	2.28	40.78	3.4	54.83	4.69
26.96	2.31	41.16	3.44	55.08	4.72
27.34	2.33	41.39	3.47	55.46	4.76
27.63	2.36	41.72	3.51	55.82	4.8
27.83	2.39	42.15	3.55	56.14	4.82
28.17	2.42	42.52	3.58	56.59	4.86
28.54	2.45	42.93	3.62	56.8	4.88
28.83	2.47	43.25	3.64	57.07	4.89
29.26	2.5	43.54	3.67	57.45	4.93
29.55	2.53	43.93	3.7	57.79	4.98
29.77	2.54	44.33	3.72	58.2	5.02
30.08	2.55	44.74	3.72	58.55	5.05
30.52	2.58	45.09	3.77	58.76	5.09
30.88	2.64	45.32	3.82	58.97	5.13
31.32	2.67	45.75	3.85	59.34	5.17
31.56	2.69	46.15	3.88	59.67	5.19

Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)
59.98	5.21	46.64	8.22
60.41	5.25	46.64	8.29
60.64	5.27	46.57	8.35
60.8	5.28	46.42	8.4
61.01	5.33	46.21	8.45
61.28	5.4	46.13	8.55
61.61	5.44	45.97	8.62
61.86	5.47	45.5	8.71
62.21	5.52	45.32	8.77
62.48	5.56	45.29	8.8
62.61	5.59	45.24	8.89
62.8	5.63	45.11	8.98
63.03	5.66	44.83	9.07
63.28	5.67	44.51	9.13
63.47	5.76	44.45	9.18
63.49	5.82	44.49	9.21
62.31	5.94		
60.99	6.04		
60.8	6.08		
60.61	6.18		
60.45	6.27		
60.42	6.33		
60.37	6.39		
60.34	6.44		
60.16	6.48		
59.89	6.58		
59.27	6.68		
57.61	6.81		
55.6	6.99		
54.74	7.1		
54.35	7.17		
51.69	7.37		
47.34	7.65		
46.97	7.77		
46.86	7.85		
46.81	7.92		
46.76	7.98		
46.66	8.01		
46.64	8.08		
46.63	8.16		

APPENDIX A2

LOAD-DEFLECTION DATA (BEFORE STRENGTHENING FOR BEAM B1)

Load (kN)	**Deflection (mm)**	**Load (kN)**	**Deflection (mm)**
0	0	16.78	1.4
0	0	17.67	1.44
0.01	0	18.32	1.49
0	0	18.78	1.54
0	0	19.27	1.58
0	0	19.55	1.62
-0.06	-0.01	19.76	1.66
-0.05	-0.01	19.93	1.68
-0.04	-0.01	20.13	1.75
-0.04	-0.01	20.61	1.81
-0.03	-0.01	21.24	1.85
-0.02	-0.01	21.98	1.89
-0.07	-0.01	22.48	1.94
-0.04	-0.01	22.75	1.97
-0.04	-0.01	22.65	1.97
-0.04	-0.01	22.64	1.97
-0.01	-0.01	22.52	1.97
-0.03	-0.01	22.46	1.97
-0.04	-0.01	22.46	1.97
-0.02	-0.01	22.39	1.97
-0.01	-0.01	22.22	1.98
0	-0.01	22.25	1.98
0.01	-0.01	22.31	1.98
0	-0.01	22.27	1.98
-0.02	-0.01	22.18	1.98
-0.02	-0.01	22.12	1.98
0.01	0	22.12	1.98
0.01	0	22.04	1.98
0.08	0.01	21.99	1.98
0.14	0.01		
0.2	0.02		
0.26	0.04		
0.29	0.04		
0.4	0.06		
0.45	0.08		
0.65	0.09		

APPENDIX A3

LOAD-DEFLECTION DATA (AFTER STRENGTHENING FOR BEAM B1)

Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)
0	0	5.93	0.45	19.6	1.46
0	0	6.12	0.48	20.16	1.49
0.49	-0.01	6.38	0.5	20.55	1.51
0.53	-0.01	7.25	0.53	20.84	1.52
0.58	-0.01	7.97	0.56	21.2	1.56
0.74	-0.01	8.35	0.57	21.58	1.61
0.89	0	8.72	0.6	22.07	1.64
1.1	0	9.07	0.63	22.38	1.67
1.24	0.01	9.3	0.66	22.72	1.7
1.37	0.02	9.39	0.68	23.21	1.74
1.45	0.03	9.53	0.71	23.66	1.77
1.52	0.04	9.62	0.73	24.11	1.8
1.56	0.05	9.75	0.75	24.41	1.83
1.59	0.05	9.96	0.79	24.75	1.85
1.64	0.05	10.36	0.82	25.18	1.89
1.66	0.06	11.1	0.85	25.58	1.9
1.7	0.06	11.91	0.87	26.03	1.94
1.75	0.07	12.39	0.9	26.29	2
1.8	0.08	12.8	0.93	26.74	2.01
1.85	0.08	13.03	0.96	27.2	2.03
1.88	0.09	13.25	0.99	27.67	2.07
1.93	0.09	13.41	1.02	28.06	2.11
2.03	0.11	13.6	1.04	28.32	2.14
2.46	0.13	13.79	1.07	28.76	2.19
2.76	0.14	14.15	1.1	29.19	2.22
3.39	0.17	14.47	1.11	29.63	2.25
3.83	0.18	15.11	1.13	30.01	2.28
4.14	0.2	15.94	1.16	30.31	2.3
4.38	0.23	16.34	1.21	30.8	2.33
4.69	0.25	16.85	1.24	31.21	2.38
4.95	0.28	17.2	1.26	31.71	2.42
5.13	0.3	17.31	1.29	32.05	2.46
5.31	0.32	17.53	1.32	32.39	2.5
5.43	0.34	17.67	1.35	32.87	2.54
5.57	0.34	17.94	1.38	33.26	2.58
5.7	0.38	18.39	1.41	33.8	2.61
5.79	0.42	18.97	1.44	34.12	2.65

Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)
34.59	2.68	54.39	4.23	70.58	5.99
35.14	2.69	54.96	4.25	70.87	6.04
35.7	2.74	55.37	4.28	71.14	6.08
36.03	2.8	55.8	4.35	71.56	6.13
36.5	2.83	56.32	4.39	71.85	6.17
36.96	2.86	56.88	4.42	71.88	6.22
37.48	2.9	57.32	4.47	66.07	6.58
37.87	2.94	57.75	4.51	55.96	7.17
38.26	2.98	58.36	4.55	55.6	7.27
38.84	3.01	58.94	4.58	55.37	7.35
39.42	3.05	59.32	4.62	54.05	7.5
39.8	3.07	59.79	4.64	52.35	7.68
40.15	3.08	60.24	4.66	49.45	7.9
40.7	3.14	60.83	4.73	47.92	8.07
41.2	3.2	61.22	4.77	47.82	8.15
41.67	3.23	61.65	4.81	47.73	8.23
42.07	3.27	62.25	4.85	47.49	8.34
42.66	3.31	62.8	4.9	47.46	8.43
43.23	3.36	63.17	4.94	47.14	8.51
43.65	3.38	63.62	4.97	46.66	8.59
44.03	3.42	64.16	5	46.54	8.7
44.52	3.45	64.69	5.03	46.07	8.81
45	3.47	65.1	5.04	45.83	8.9
45.55	3.5	65.53	5.11	45.68	8.96
45.9	3.57	66.11	5.16	45.7	9.07
46.46	3.61	66.66	5.2	45.69	9.15
47.03	3.65	67.02	5.25	45.68	9.23
47.49	3.69	67.29	5.29	45.69	9.3
47.86	3.73	67.69	5.34	45.69	9.34
48.36	3.77	68.07	5.38	45.73	9.45
48.93	3.81	68.46	5.41		
49.43	3.84	68.53	5.48		
49.77	3.86	67.28	5.62		
50.37	3.9	67.52	5.68		
51.02	3.96	68.01	5.73		
51.45	4	68.57	5.76		
51.86	4.04	68.95	5.8		
52.37	4.08	69.23	5.83		
52.87	4.13	69.68	5.9		
53.39	4.16	70.08	5.95		
53.84	4.19	70.08	5.95		

APPENDIX A4

LOAD-DEFLECTION DATA (BEFORE STRENGTHENING FOR BEAM B2)

Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)
0	0	12.82	0.98
0	0	13.64	1.02
-0.01	0	14.53	1.05
0.25	0.04	15.23	1.07
0.3	0.05	15.66	1.13
0.33	0.06	15.96	1.19
0.44	0.07	16.16	1.24
0.53	0.09	16.6	1.3
0.7	0.1	17.32	1.34
1.19	0.11	18.35	1.38
1.5	0.13	18.96	1.43
2.03	0.14	19.28	1.45
2.42	0.16	19.75	1.49
2.76	0.18	19.74	1.52
3.09	0.21	19.6	1.53
3.49	0.23	19.53	1.54
3.75	0.26	19.48	1.54
3.88	0.27	3.82	0.65
4.11	0.28	-1.33	0.31
4.28	0.33	-1.33	0.3
4.54	0.38	-1.26	0.3
5.11	0.41	-1.29	0.3
6.13	0.45		
6.9	0.49		
7.33	0.53		
7.7	0.56		
7.93	0.59		
8.11	0.63		
8.36	0.66		
9.08	0.67		
10.2	0.71		
10.95	0.77		
11.44	0.81		
11.73	0.86		
11.97	0.9		
12.26	0.95		

APPENDIX A5

LOAD-DEFLECTION DATA (AFTER STRENGTHENING FOR BEAM B2)

Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)
0	0	1.47	0.01	6.55	0.29
0	0	1.59	0.01	7.37	0.3
-0.51	0	1.59	0.02	8.15	0.31
-0.42	0	1.64	0.02	8.6	0.32
-0.36	0	1.7	0.03	8.93	0.33
-0.23	0	1.71	0.03	9.3	0.34
-0.07	0	1.73	0.03	9.5	0.36
0.04	0	1.76	0.03	9.62	0.37
0.14	0	1.78	0.04	9.74	0.38
0.32	0	1.82	0.05	9.84	0.39
0.41	0	1.86	0.05	9.99	0.39
0.51	0	1.87	0.06	10.23	0.4
0.58	0	1.87	0.06	10.69	0.42
0.61	0	1.96	0.07	11.66	0.45
0.77	0	1.94	0.07	12.29	0.47
0.83	0	1.99	0.08	12.79	0.49
0.9	0	2.03	0.09	13.09	0.51
1	0	2.1	0.09	13.37	0.52
0.96	0	2.19	0.1	13.52	0.53
1.08	0	2.36	0.11	13.66	0.55
1.16	0	2.72	0.11	13.85	0.57
1.28	0.01	3.21	0.13	14.07	0.58
1.18	0.01	3.69	0.14	14.37	0.6
1.23	0.01	4.11	0.14	14.76	0.62
1.18	0.01	4.35	0.15	15.87	0.63
1.1	0.01	4.57	0.16	16.46	0.65
1.09	0.01	4.91	0.18	16.97	0.67
1.05	0.01	5.19	0.19	17.33	0.68
1.1	0	5.34	0.2	17.51	0.69
1.08	0	5.45	0.21	17.61	0.71
1.15	0	5.6	0.22	17.79	0.73
1.21	0.01	5.74	0.23	18.04	0.75
1.31	0.01	5.88	0.24	18.42	0.77
1.31	0.01	5.99	0.25	18.96	0.78
1.34	0.01	6.16	0.27	19.79	0.79
1.47	0.01	6.34	0.28	20.43	0.8

Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)
20.75	0.82	32.28	1.41	50.75	2.5
21.03	0.86	32.64	1.42	51.29	2.54
21.46	0.87	33.13	1.44	51.69	2.57
21.84	0.89	33.55	1.47	52.06	2.6
22.3	0.91	34.05	1.49	52.53	2.64
22.65	0.93	34.44	1.51	52.91	2.66
22.99	0.95	34.98	1.54	53.36	2.69
23.46	0.97	35.5	1.56	53.7	2.72
23.87	1	36.04	1.57	54.15	2.74
24.34	1.01	36.37	1.59	54.65	2.76
24.64	1.03	36.85	1.64	55.12	2.82
25.06	1.06	37.29	1.67	55.52	2.85
25.46	1.08	37.79	1.69	55.85	2.88
25.91	1.1	38.16	1.72	56.36	2.91
26.35	1.12	38.58	1.75	56.81	2.95
26.69	1.14	39.1	1.78	57.32	2.98
27.24	1.16	39.66	1.8	57.64	3.02
27.68	1.17	40.05	1.83	58.07	3.04
28.23	1.18	40.39	1.86	58.55	3.07
28.55	1.22	40.89	1.88	59.14	3.11
29.03	1.25	41.36	1.91	59.5	3.13
29.51	1.28	41.84	1.93	59.82	3.14
30.03	1.3	42.21	1.95	60.26	3.19
30.38	1.32	42.7	1.96	60.7	3.24
30.8	1.35	43.22	1.99	61.2	3.27
31.34	1.37	43.76	2.04	61.55	3.3
31.86	1.4	44.08	2.07	61.98	3.34
32.28	1.41	44.54	2.1	62.51	3.37
32.64	1.42	44.96	2.13	63.06	3.41
33.13	1.44	45.49	2.16	63.38	3.44
33.55	1.47	45.86	2.19	63.77	3.47
34.05	1.49	46.28	2.21	64.27	3.5
34.44	1.51	46.81	2.24	64.73	3.52
34.98	1.54	47.3	2.27	65.14	3.55
35.5	1.56	47.74	2.29	65.44	3.61
36.04	1.57	48.06	2.32	65.89	3.65
36.37	1.59	48.48	2.34	66.4	3.68
36.85	1.64	48.95	2.35	66.8	3.73
37.29	1.67	49.47	2.4	67.11	3.77
37.79	1.69	49.8	2.44	67.29	3.81
31.86	1.4	50.19	2.48	67.56	3.85

Load (kN)	**Deflection (mm)**	**Load (kN)**	**Deflection (mm)**
67.81	3.89	70.74	5.85
68.14	3.91	70.66	5.92
68.43	3.95	70.5	6.02
68.59	4.03	70.12	6.11
68.95	4.07	69.71	6.2
69.17	4.12	69.33	6.28
69.45	4.16	68.89	6.4
69.84	4.2	68.3	6.51
70.21	4.23	67.9	6.6
70.66	4.27	67.78	6.66
71.04	4.3	67.61	6.76
71.31	4.31	67.41	6.85
71.67	4.38	66.81	6.97
72.05	4.43	58.78	7.57
72.48	4.46	55.96	7.83
72.86	4.5	55.59	7.95
73.16	4.54	55.45	8.05
73.61	4.59	55.19	8.14
74.02	4.62	54.78	8.22
74.49	4.66	54.51	8.34
74.87	4.69	54.46	8.43
75.11	4.7	54.39	8.51
75.4	4.77	54.31	8.58
75.78	4.82	54.36	8.63
76.15	4.86	54.51	8.72
76.56	4.91	54.55	8.79
76.88	4.96	54.61	8.86
77.09	4.99	54.59	8.91
77.42	5.03	54.17	8.93
77.76	5.07		
77.99	5.09		
78.07	5.17		
77.6	5.27		
74.14	5.52		
70.98	5.78		
70.74	5.85		
70.66	5.92		
70.5	6.02		
70.12	6.11		
69.71	6.2		

APPENDIX A6

LOAD-DEFLECTION DATA (BEFORE STRENGTHENING FOR BEAM B3)

Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)
0	0	1.25	0.11	11.49	0.71
0	0	1.28	0.12	12.06	0.73
0	0	1.3	0.12	12.44	0.76
0.07	0	1.36	0.13	12.68	0.78
0.08	0	1.41	0.13	12.9	0.79
0.07	0	1.51	0.14	13.18	0.85
0.05	0	1.55	0.15	13.47	0.9
0.14	0	1.7	0.16	13.97	0.92
0.13	0	2.13	0.17	14.71	0.96
0.17	0	2.47	0.18	15.48	1
0.23	0	2.42	0.19	15.98	1.05
0.33	0	1.82	0.18	16.52	1.08
0.32	0	2.36	0.19	16.79	1.11
0.42	0	2.94	0.21	17.01	1.15
0.45	0	3.27	0.22	17.16	1.17
0.47	0	3.5	0.23	17.56	1.18
0.56	0	3.77	0.24	18.05	1.24
0.61	0	4.1	0.26	18.83	1.3
0.67	0.01	4.36	0.28	18.89	1.31
0.67	0	4.6	0.3	18.76	1.32
0.74	0.01	4.78	0.31	18.59	1.32
0.81	0.01	4.93	0.33	18.43	1.32
0.82	0.01	5.07	0.35		
0.85	0.01	5.23	0.37		
0.94	0.01	5.39	0.38		
0.94	0.01	5.74	0.39		
0.99	0.01	6.12	0.4		
1.04	0.02	7.1	0.41		
1.02	0.03	7.76	0.46		
1	0.04	8.16	0.49		
1.1	0.06	8.55	0.52		
1.06	0.07	8.79	0.54		
1.11	0.08	8.94	0.57		
1.13	0.08	9.12	0.6		
1.16	0.09	9.26	0.62		
1.21	0.1	9.77	0.65		
1.22	0.1	10.51	0.68		

APPENDIX A7

LOAD-DEFLECTION DATA (AFTER STRENGTHENING FOR BEAM B3)

Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)
0	0	9.09	0.54	24.58	1.21
0	0	8.77	0.56	25.96	1.24
1.67	0.03	9.13	0.58	25.43	1.26
1.65	0.04	9.18	0.59	26.37	1.29
1.49	0.04	9.25	0.62	27.01	1.31
1.69	0.05	9.45	0.63	27.36	1.33
2.25	0.07	9.55	0.66	27.74	1.35
3.22	0.08	9.74	0.67	28.68	1.37
3.41	0.09	11.6	0.68	29.57	1.39
3.5	0.11	15.46	0.69	29.95	1.41
3.05	0.13	15.13	0.71	30.19	1.44
3.44	0.13	15.89	0.74	29.48	1.45
3.46	0.14	15.29	0.76	29.02	1.47
3.85	0.16	15.86	0.78	29.67	1.48
4.38	0.18	16.21	0.8	30.04	1.52
5.08	0.18	17.25	0.81	29.97	1.54
5.97	0.19	17.47	0.83	30.5	1.55
6.19	0.21	17.81	0.86	30.58	1.57
6.08	0.23	18.27	0.87	31.19	1.6
5.15	0.24	18.07	0.89	31.33	1.62
3.08	0.27	18.88	0.91	31.48	1.64
3.05	0.28	19.49	0.93	32.68	1.67
3.63	0.29	20.11	0.95	32.95	1.69
4.31	0.3	20.89	0.96	33.38	1.72
7.57	0.31	21.3	0.98	33.6	1.75
8.73	0.34	22.16	1	33.46	1.79
6.72	0.37	22.66	1.02	33.5	1.82
6.33	0.38	23.33	1.04	33.97	1.84
6.5	0.39	22.94	1.06	34.61	1.85
8.01	0.41	22.9	1.07	35.74	1.87
8.14	0.43	23.2	1.08	35.63	1.9
8.3	0.45	24.17	1.1	36.21	1.94
7.89	0.47	24.61	1.14	36.04	1.96
8.21	0.49	21.76	1.16	35.88	1.99
9.16	0.51	22.88	1.17	36.63	2.01
9.5	0.52	23.71	1.2	36.83	2.03

Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)
37.01	2.07	46.87	3.1	59.5	4.05
36.08	2.08	46.09	3.13	60.24	4.07
36.07	2.11	46.49	3.16	60.39	4.1
33.73	2.16	47.3	3.17	61.19	4.12
34.19	2.18	47.37	3.16	61.97	4.14
34.53	2.2	48.1	3.17	62.46	4.15
35.25	2.23	47.85	3.2	62.59	4.17
34.96	2.24	48.16	3.23	63.14	4.18
36.97	2.25	49.14	3.28	62.92	4.19
37.56	2.29	49.42	3.36	64.06	4.19
36.84	2.32	50.8	3.34	68.31	4.2
37.21	2.35	51.23	3.36	67.29	4.24
36.81	2.38	51.55	3.38	66.59	4.28
37.27	2.4	51.28	3.4	66.35	4.31
37.65	2.42	52.6	3.41	66.47	4.34
35.73	2.45	53.94	3.43	67	4.36
38.37	2.48	53.65	3.48	68.24	4.4
39.03	2.5	52.98	3.51	68.82	4.43
38.82	2.53	53.03	3.54	69.89	4.45
37.26	2.55	53.28	3.56	70.04	4.48
36.81	2.58	53.9	3.59	71.08	4.51
38.49	2.61	54.24	3.62	70.5	4.53
38.87	2.62	54.17	3.64	70.94	4.56
42.05	2.63	52.88	3.66	71.41	4.58
42.67	2.66	51.45	3.69	71.85	4.59
42.69	2.7	51.57	3.72	71.67	4.61
43.06	2.73	51.6	3.74	71.7	4.66
44.2	2.76	53.13	3.77	71.88	4.7
43.6	2.79	56.09	3.79	71.82	4.73
41.31	2.82	55.08	3.8	73.34	4.76
41.9	2.85	54.97	3.81	72.89	4.8
41.18	2.87	55.28	3.84	73.33	4.82
42.11	2.9	57.98	3.88	75.77	4.85
42.45	2.92	57.46	3.92	75.94	4.88
42.89	2.95	58.34	3.94	76.1	4.91
43.32	2.97	58.3	3.97	76.37	4.95
44.01	3	58.34	3.94	76.1	4.91
44.68	3.02	58.3	3.97	76.37	4.95
45.36	3.03	58.56	4	77.21	4.97
46.04	3.06	58.7	4.03	76.87	5

Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)
77.38	5.06	90.68	6.2
77.93	5.1	94.37	6.25
78.77	5.1	93.71	6.29
79.17	5.12	93.86	6.32
78.91	5.17	96.21	6.37
79.57	5.2	94.73	6.44
79.76	5.23	88.57	6.85
79.8	5.26	76.77	7.53
79.72	5.29	74.07	7.69
80.01	5.33	73.45	7.85
81.89	5.36	67.1	8.07
82.77	5.37	67.2	8.16
83.39	5.42	65.13	8.25
84.93	5.47	66.22	8.32
81	5.52	64.61	8.39
77.33	5.59	65.3	8.44
77.33	5.89	68.93	8.48
77.23	5.54	68.99	8.51
79.4	5.55	69.14	8.59
82.67	5.59	69.09	8.65
82.72	5.61	67.61	8.7
82.99	5.65	68.87	8.76
83.07	5.68	68.52	8.81
82.87	5.71	68.68	8.86
83.2	5.74	67.78	8.89
84.33	5.76	67.41	8.98
84.53	5.78	64.63	9.05
85.67	5.83	64.96	9.13
88.77	5.88	67.07	9.19
88.97	5.9	66.93	9.24
89.83	5.94	66.15	9.32
90.38	5.98	63.46	9.43
89.58	6	62.18	9.5
90.82	6.04	61.74	9.51
91.46	6.07	62.6	9.55
90.13	6.1	62.49	9.6
92.93	6.13	62.39	9.65
91.39	6.15	63.25	9.66
90.48	6.14	63.54	9.66
88.74	6.15	63.38	9.67

APPENDIX A8

THEORETICAL LOAD-DEFLECTION DATA (BASED ON ACI-318)

Load (kN)	I=4.178 x 10^7 mm^4	
	E=200GPa (mm)	E=11.76 GPa (mm)
0	0.0000	0.0000
5	0.0390	0.6640
10	0.0781	1.3280
15	0.1171	1.9920
20	0.1562	2.6560
25	0.1952	3.3201
30	0.2343	3.9841
35	0.2733	4.6481
40	0.3124	5.3121
45	0.3514	5.9761
50	0.3904	6.6401
55	0.4295	7.3041
60	0.4685	7.9681
65	0.5076	8.6321
70	0.5466	9.2961
75	0.5857	9.9602
80	0.6247	10.6242
85	0.6637	11.2882
90	0.7028	11.9522
95	0.7418	12.6162
100	0.7809	13.2802