SWANSEA UNIVERSITY

[illegible]

[illegible] BIN MOHD [illegible]

Swansea University

Civil and Computational Engineering Centre

C2EC

CRACK CRONOLOGY OF REINFORCED CONCRETE BEAM UNDER IMPACT LOADS

Zainorizuan Bin Mohd Jaini
393235

MSc Computer Modelling and Finite Element in Engineering Mechanics

October 2008

A dissertation submitted in fulfilment of the requirement for the award of the MSc Computer Modelling and Finite Elements in Engineering Mechanics.

Civil and Computational Engineering Centre
Faculty of Engineering
Swansea University
Singleton Park, SA2 8PP
Swansea, Wales, United Kingdom.

Declaration

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any other degree.

Signed .... (candidate)

Date ....15/10/2008..

Statement 1

This thesis is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

Signed .... (candidate)

Date ....15/10/2008..

Statement 2

I hereby give consent for my thesis, if accepted, to be available for photocopying and for inter-library loan, and for the title and summary to be made available to outside organisations.

Signed .... (candidate)

Date ....15/10/2008..

Abstract

Impact is one of dynamic transient loadings which is contribute to structure damages such as cracks and frequently generate a dangerous effect to reinforced concrete structures. Nowadays, several areas of civil engineering incorporate the need to be able to predict such structural behaviour under impact loading. Previous researchers have noted that concrete structures under impact loading show different behaviour from that under static loading. This study presents a three-dimensional nonlinear finite element simulation of the reinforced concrete beams subjected low-velocity impact loading. The main objective of this study is to determine the crack chronology specifically in time and location. Beam with geometry 1.5m long, 0.2m depth and 0.1m width has been modelled by ELFEN. Numerical modelling and ELFEN code is based on previous study of the reinforced concrete beam under impact loading conducted by P.J. Thiele (2005). This study has involved 16 models which are divided into three factors of simulation, that are modelling factors to determine the most suitable model, support conditions to study crack chronology caused by the rigid support, support material and support thickness, and impactor factors to determine the crack chronology caused by various velocities and densities. From the results, the main crack modes are spalling crack at the top surface of beam and scabbing crack on the bottom surface of beam. It is found in this study that there are two categories of crack chronologies. First is crack happens at the bottom surface of beam recognized as scabbing crack and then followed by the beam crack at the support area and finally spallation crack. Another category of crack chronology is occurs as scabbing crack, then spallation crack and finally beam crack at the support area. Cracks due to impact loading can be described by wave theory. Scabbing crack caused by the direct impact wave and compression condition at the rare area of beam. Spallation crack occurs by two reasons, the impact wave propagate to the support area and the rarefaction wave that reflected from support. Besides that, spallation crack also occur related to its global deformation. For the purpose of validation, the results obtained from numerical simulation of the three-dimensional reinforced concrete beam, which is carried out using the finite element software ELFEN are validated by deeply literature review. There are no comparisons between experimental results. Final cracks pattern for each model is carried out to make comparison with previous study of crack behaviour where the results are obviously similar.

Acknowledgements

Foremost, I would like to express my deep sincere thanks and gratitude to my project supervisor, Dr. Y. T. Feng (Reader in School of Engineering) for great assistance in undertaking this project. I am very grateful for all his time, guidance, advice and patience throughout progression of this project.

I also wish to express my gratitude to the Civil and Computational Engineering Centre that provide computer facilities and ELFEN software to this project.

I am particularly grateful for the scholarship awarded by the Kementerian Pengajian Tinggi Malaysia (Ministry of Higher Education Malaysia) and University Tun Hussein Onn Malaysia (UTHM) especially to Dr. Abd Aziz Abd Samad, without which I would not have been able to stay at Swansea University to complete this study.

Also a special thanks to entire friends especially Ms. Fen Fai and Mr. Gong Zheng for their support, kindest help, work co-operation, knowledge and information sharing, and confidence, also thanks to those that had direct and indirectly contribute in my preparation for this project.

Finally, my special thanks to my parents for their continuing support, encouragement and provide me the great opportunity in Swansea University. Without them I would not be where I am today. They always have been a source of my inspiration.

Thank you.

Table of Contents

Declarations i
Abstract ii
Acknowledgements iii
Table of Contents iv
List of Figures vi
List of Tables ix

Chapter 1 - Introduction 1
1.1 Background of Study 3
1.2 Objective of Study 4

Chapter 2 - Literature Review 6
2.1 Finite Element Modelling and Simulation 7
2.2 Impact Loading and The Damages 12
2.3 Reinforced Concrete Beam and Crack Behaviour 15

Chapter 3 - Methodology 21
3.1 Finite Element Modelling by ELFEN 24
3.2 Modelling 25
3.3 Result Analysis 29
3.4 Result Validation 29

Chapter 4 - Experimental and Simulation Works 30
4.1 Experimental Work 31
4.2 Simulation Work 34
4.3 Result Comparison 36

Chapter 5 - Computational Model 39
5.1 Material Properties 40
5.1.1 Concrete 40
5.1.2 Steel Reinforcement 41
5.1.3 Impactor 43
5.1.4 Plywood 43
5.2 ELFEN Input 44
5.2.1 Geometric Model 44

5.2.2 Loading 45
5.2.3 Constraint 46
5.2.4 Material 46
5.2.5 Mesh 48
5.2.6 Data Control 48
5.2.7 ELFEN Code Modification 49

Chapter 6 - Results and Analysis 51

6.1 Modelling Factors: Meshing size 52
6.2 Modelling Factors: Interface Between Support and Beam 58
6.3 Support Conditions: Rigid Support 63
6.4 Support Conditions: Support Material 69
6.5 Support Conditions: Support Thickness 74
6.6 Impactor Factors: Impact Velocity 79
6.7 Impactor Factors: Density of Impactor 84

Chapter 7 – Discussion, Conclusion and Recommendation 89

7.1 Discussion 90
7.1.1 Results of Finite Element Simulation 90
7.1.2 Crack Chronology 93
7.1.3 Scabbing and Spallation Crack Mechanism 94
7.2 Conclusion 99
7.1 Recommendation 100

References 101

List of Figures

Figure	Title	Page
2.1:	Example of three dimensional modelling of the beam and the impact block with different size mesh.	9
2.2:	Cross section of the reinforced concrete structure with layers of the concrete.	11
2.3:	Impact phenomena for concrete and reinforced concrete structures, spallation on impact face, scabbing on back face and perforation.	13
2.4:	The effect of oblique impact on the concrete damage.	14
2.5:	The bonding between concrete and reinforcing	16
2.6:	Propagation of cracks in beam as obtained by Abbas et al.	18
2.7:	Predicted crack pattern for beam analysed by Thabet and Haldane	19
2.8:	Crack pattern for beam with and without shear rebar sketched by Kishi et al	19
2.9:	Crack pattern by laboratory experimental	20
2.10:	Crack pattern by Bere's model	20
2.11:	Final crack pattern by Thiele's model	20
3.1:	Flow chart for the whole process of study	22
3.2:	Flow chart for beam modelling in ELFEN	23
3.3:	Example of reinforced concrete beam models	28
4.1:	Schematic diagram of the reinforced concrete beam (experimental setup)	31
4.2:	Details of reinforcement arrangement used in experimental study	32
4.3:	Beam crack propagation in scabbing area, struck by flat impactor	33
4.4:	Geometry of lines that form the concrete volume and reinforcements	35
4.5:	Meshing that used in the Tiele's model	35
4.6:	Steel bars arrangement in the Tiele's model	35
4.7:	Different support condition used in Thiele's model	36
4.8:	Impact force time history for experimental result	37
4.9:	Impact force time history for simulation results by Thiele	37
4.10:	Crack formation obtained by experimental study	38

4.11:	Crack formation obtained by simulation study	38
5.1:	Strain rate dependency of concrete material	40
5.2:	Hardening properties of mild and high yield steel reinforcement	42
5.3:	Line elements	44
5.4:	Surface elements from line combination	44
5.5:	Volume elements created from surface	45
5.6:	Impact loading in vertical direction	45
5.7:	Boundary conditions for support, impact and beam	46
5.8:	Steel reinforcements defined as line material	47
5.9:	Wall define for inner part of beam	47
5.10:	Volumes of beam defined as scab and spall concrete	47
5.11:	Volume material for support, plywood and impactor	47
5.12:	Fine meshing size	48
5.13:	Corse meshing size, remeshing	48
6.1:	Crack chronology for Model 1A with mesh size 0.02mm	53
6.2:	Crack chronology for Model 2A with mesh size 0.03mm	54
6.3:	Crack chronology for Model 3A with mesh size 0.04mm	55
6.4:	Final cracks pattern for Model 1A, Model 2A and Model 3A	56
6.5:	Crack chronology for Model 2B	59
6.6:	Crack chronology for Model 3B	60
6.7:	Final cracks pattern for Model 1B, Model 2B and Model 3B	61
6.8:	Cracks chronology for Model 1C	64
6.9:	Cracks chronology for Model 2C	65
6.10:	Cracks chronology for Model 3C	66
6.11:	Final crack pattern for Model 1C, Model 2C and Model 3C	67
6.12:	Cracks chronology for Model 2D	70
6.13:	Cracks chronology for Model 3D	71
6.14:	Final crack pattern for Model 1D, Model 2D and Model 3D	72
6.15:	Cracks chronology for Model 2E	75
6.16:	Crack chronology for Model 3E	76
6.17:	Final cracks pattern for Model 1E, Model 2E and Model 3E	77
6.18:	Crack chronology for Model 2F	80
6.19:	Crack chronology for Model 3F	81
6.20:	Final cracks pattern for Model 1F, Model 2F and Model 3F	82
6.21:	Crack chronology for Model 2G	85
6.21:	Crack chronology for Model 2G	86

6.23:	Final cracks pattern for Model 1G, Model 2G and Model 3G	87
7.1:	Spallation occur at centre of rotational velocity vector	96
7.2:	Spallation crack occur at positive area of deflection	97
7.3:	Damage indicator during spallation crack	97

List of Tables

Table	Title	Page
3.1:	Details description about Model 1A till Model 3B	26
3.2:	Details description about Model 1C till Model 3G	27
5.1:	Concrete linear material properties	40
5.2:	Strain rate dependency of concrete material	41
5.3:	Steel material properties	41
5.4:	Hardening properties of mild and high yield steel reinforcement	42
5.4:	Impact mass material properties for iron steel	43
5.6:	Plywood material properties	43
5.7:	Geometry properties for steel reinforcement according the sizes of bar	49
5.8:	The discrete element contact data	50
6.1:	The cracks chronology for different mesh size	52
6.2:	Cracks in time, (microsecond) for different mesh size	52
6.3:	The cracks chronology for support modelling condition	58
6.4:	Cracks in time, (microsecond) for support modelling condition	58
6.5:	The cracks chronology for rigid support conditions	63
6.6:	Cracks in time, (microsecond) for rigid support conditions	63
6.7:	The cracks chronology for different support material	69
6.8:	Cracks in time, (microsecond) for rigid support conditions	69
6.9:	The cracks chronology for different support thickness	74
6.10:	Cracks in time, (microsecond) for different support thickness	74
6.11:	The cracks chronology for various velocities of impact	79
6.12:	Cracks in time, (microsecond) for various velocities of impact	79
6.13:	The cracks chronology for various densities of impactor	84
6.14:	Cracks in time, (microsecond) for various densities of impactor	84
7.1:	Vector velocity for first category crack chronology	94
7.2:	Vector velocity for second category crack chronology	94

Chapter 1

Introduction

1.0 Introduction

Impact or sudden loading is one of dynamic factors that play an important role in structural design. However, not until recently, buildings that were designed to resist impact loads were predominantly limited in the military sector, defences nuclear shell and mountain area buildings. Unlike earthquakes or vibration conditions, impact possesses a multi-uniqueness characteristic that should be taken into account accurately in engineering design. However, analysis and design of structures subjected to dynamic loading are often very complex. Such analysis becomes more difficult when associated with nonlinear materials such as reinforced concrete. Consequently, the responses of concrete structures to transient dynamic loading have been explored extensively for both civil and military applications. In terms of impact loading, understanding of the interaction between concretes and impact or explosive loading is essential to protect fortifications **[1]**. The damage of impact is usually caused by projectiles, vehicle crashes, falling objects. Generally, in structural engineering, impact loading is mostly accounted for walls, beams and slabs in both steel and concrete.

Reinforced concrete beams are among the most typical structural elements. In spite of the large number of beams designed and built, it is crucial to take impact load into consideration for the behaviour of the beams **[2]**. That is the main reason that there has been a rapid growing of interest in the past few years among the engineering communities to understand the response of the reinforced concrete structures subjected to extreme loads due to impact and blast. Although these severe transient dynamic loads are rare in occurrence for most structures, their effect can result in random and catastrophic structural failures. Some examples are listed in **[2]** and **[3]**, which should suffice as evidence in concerning the importance of impact study. Reinforced concrete structures are often subjected to extreme dynamic loading conditions due to direct impact. For instance, bridge piers must be designed to resist accidental impact by heavy vehicles; nuclear power plant facilities must be designed to resist aircraft impact; military structure and critical civilian infrastructure must be able to survive the impact and blast load from the conventional explosions and debris fragmentation impact. Similarly, offshore structure must be designed to sustain repeated loads from docking ships or ice burgs.

After the 'September 11' tragedy, it has become a significant issue for understanding the damage behaviour of reinforced concrete structures under impact loading, especially in the case of an aircraft crashing into a nuclear power facility and high-rise building, and there is an urgent need to establish structural design methods for impact load. In general, structural damage to reinforced concrete structures under impact load includes the global damage and local damage. Global damage is characterized as a dynamic elasto-plastic response over a large region of the structure for a relatively long period. Quite a good appraisal of global damage is possible with the conventional nonlinear finite element method using a time-response dynamic analysis. Local damage to reinforced concrete structures may include the spalling of concrete from the front face, scabbing of concrete from the rear face and perforation of the missile through the structure. Because of an extremely short stress wave occurred immediately after impact may have caused this behaviour, it has been rather difficult to derive an analytical method that estimates the local damage. Therefore, until now, the local damage to reinforced concrete structures has been evaluated mainly with empirical formulas that are derived from various types of impact tests. However, in recent years, an advancement of research in the field of numerical analysis on fracture mechanics has led to proposals and trials of various fracture analysis methods.

1.1 Background of Study

Dynamic as well as impact in concrete structures is considered in the design aspect for critical usage. As a result, the studies about this situation were conducted a long time ago. Most research at the time were about laboratory experiments involving the prototypes and model specimen. The early study of the concrete under the impact loading only focused on the interest of materials such as the strength, ductility, toughness and durability to understand how these concrete material properties are able to shield themselves with minimum failures from the impact. For many years, concrete structures have been studied to obtain the capability of endurance of impact throughout the experiments. However, in recent years, there has been an increased utilisation of the multi-physic simulation software packages especially using the finite element approach. Finite element analysis, arguably, is the most well known type of numerical simulations, and has become a popular tool for simulating the behaviour and response of complex structures. This yields from the advances in the combination of both the computer power and mathematical techniques as they have led us to more sophisticated investigations **[4]**.

There have been a number of studies on the impact resistance of reinforced concrete members in the past decades. Majority of these investigations focused on the impact behaviour of structural members failing in flexure **[5]**. Review shows that the main work on the impact behaviour of reinforced concrete can be classified into two categories, those studying the behaviour of reinforced concrete material and those studying the impact experiments in order to comprehend the behaviour of the reinforced concrete structure under the impact loading **[6]**. Most of the past researchers such as Kasai, Hanchak, Dancygier, Yankelevsky, Gomez and Shuka **[7]** have performed studies earlier on the penetration and perforation of reinforced concrete into experimental, empirical, analytical and numerical simulation. The complexity of the properties of concrete makes it very difficult to develop a relatively accurate material model to predict numerically the impact damage by a projectile. Consequently, Aradh (1982), Laine (1990), McMahoon (1998), Yankelesky (2000), William (2001), Chu (2006) and Wang (2006) have used the finite element code and continuum damage model to calculate impact damages **[3,5,6]**. In addition, Dancygier and Yankelevsky have conducted many investigations to determine the impact behaviour with and without reinforcement **[8]**. They also have evaluated and developed several mathematical models in describing the penetration depth of the projectiles in concrete. Recently, a simple elasto-plastic finite element model for structures subjected to lateral impact loading is developed in **[9]**.

1.2 Objective of Study

The current study aims to extend the previous work on using finite element methods to simulate reinforced concrete beams under low-velocity impact loading conducted at Swansea University. This is a contribution towards a better understanding of crack developments and general behaviour that appear on reinforced concrete beams in terms of scabbing, spallation and perforation. Furthermore, this study intends to develop more accurate procedures in predicting the cracks.

The prime objective of this study is to investigate the response of reinforced concrete structures when subjected to abnormal impact loading in order to gain a better understanding of the behaviour of the structure within the nonlinear range, where extensive cracking of the reinforced concrete beam can take place in conjunction with the yielding of the steel reinforcement, resulting in mechanism leading to scabbing, spallation, penetration and possibly, complete failure. In order to achieve the general aims, the following specified objectives are proposed to be achieved.

i. To study the design of reinforced concrete beam with regard to the previous experiments and modelling works in terms of geometry, steel reinforcement and material properties.

ii. To model the three-dimensional reinforced concrete beam based on the previous designs.

iii. To simulate the reinforced concrete beam under low-velocity impact loading in various factors, modelling, supports and impactor conditions.

iv. To identify crack development patterns in time (microsecond) and to determine the level of damage.

v. To evaluate the factors affecting scabbing and spallation appearing at certain locations at certain time instants.

Chapter 2

Literature Review

2.0 Literature Review

The objectives of this chapter are to provide a background and a supporting knowledge on the scope of finite element analysis of reinforced concrete beams subjected to impact loading, and subsequent crack behaviour. Therefore, this literature review has been divided into three sub-topics to facilitate the review process. The topics are divided into finite element modelling and simulation, impact loading and the effects, and reinforced concrete structural and crack behaviour. A clear understanding of impact loading and reinforced concrete behaviour under such loading is significantly important before the finite element modelling and simulation could be conducted. Note that previous and recent investigations on impact were meant to improve the resistance of the reinforced concrete to impact loading. On the other hand, most of the impact experiments were developed in order to further understanding the behaviour of the reinforced concrete structure under impact loading.

2.1 Finite Element Modelling and Simulation

In the past, the route to gaining a confident prediction of responses on impacted structures, including near ultimate load effects of scabbing, spallation and penetration, has been hampered by both a lack of an adequate computational solution procedures and the inability of getting a good quality reports and experimental results **[5]**. In addition to that, computers were not developed yet to the standards of today. The numerical simulations require a vast amount of computational power and could take a long period of time to complete. With the continuous improvement of computer technology, the numerical models are becoming more accuracy and reliable, and also are fairly quick to attain. Computational modelling is one of the means to convert the data experiments into the computer model that makes the data more comprehensive **[10]**.

Computational modelling, including the finite element simulation, is now well accepted as the most powerful general technique for the numerical or simulation solution of many engineering problems. Its applications range from the stress analysis of solids to the solution of acoustical phenomena, neutron physics and fluid dynamic problems. Computational modelling and simulation was developed hand-in-hand with the rapid growth of the computer. In parallel with the advancement of knowledge in engineering, the finite element method (FEM) has become the most powerful method in both analysis and modelling of complex problems **[10,11]**. Computational models allow predictions of the behaviour of the problems. The models not only make it simpler for others to understand the solutions, but also predict how the problems would behave under different conditions, even without carrying out actual experiments. Consequently, computational modelling with the finite element method has been recognised as an essential tool by many successful investigators globally who enable many new and innovative products to become reality.

In particular, over the past several decades, the finite element method has turned into a popular technique in civil engineering for predicting the response of structures and materials. Finite element is a general method of structural analysis, in which the solutions of a problem in continuum mechanics could be approximated by the analysis of an assemblage of finite elements, which are interconnected at finite numbers of nodal points that represents the solution of the problem **[12]**. The improvement of computer power and advances in finite element modelling has led to the creation of sophisticated computer models that can simulate the structural materials and members with a fair degree of accuracy. Currently, the finite element method has been widely employed for solving linear elastic and elastic-plastic failure problems. Ansys, Lusas, Elfen, Abaqus and other finite element software packages have made nonlinear finite element analysis a feasible tool for evaluate, design, simulate and predict many of engineering problems. The finite element method has become a powerful computational tool which allows complex analysis of the nonlinear response of reinforced concrete structure to be carried out in a routine fashion. With this method, the importance and interaction of diverse nonlinear effects on the response of reinforced concrete structures can be studied numerically.

Basically, in the finite element method, complex structures are divided into a large number of small elements, whose stress-strain relationships can be easily approximated. The conditions of dynamic equilibrium and the boundary conditions are then enforced on all the elements. This allows the analyst to determine the displacements and stress that are associated with each element. Consequently, the behaviours and structural failures can be easily analysed for any kind of loading. Since the reinforcing bars and the concrete bear the external impact for a short duration, they can be assumed to have a good bending property that prevented them from sliding **[13]**. Hence, Y.S Tai and C.C Tang **[1]**, in the numerical simulation of reinforced concrete structure under normal impact, chose the combination approach standard in which the reinforced bar and concrete have different numbers of elements. The numbers and size of elements have contributed significantly to the results of the finite element analysis. Figure 2.1 shows the reinforced concrete beam and the impact block which was created with a different element mesh number and size.

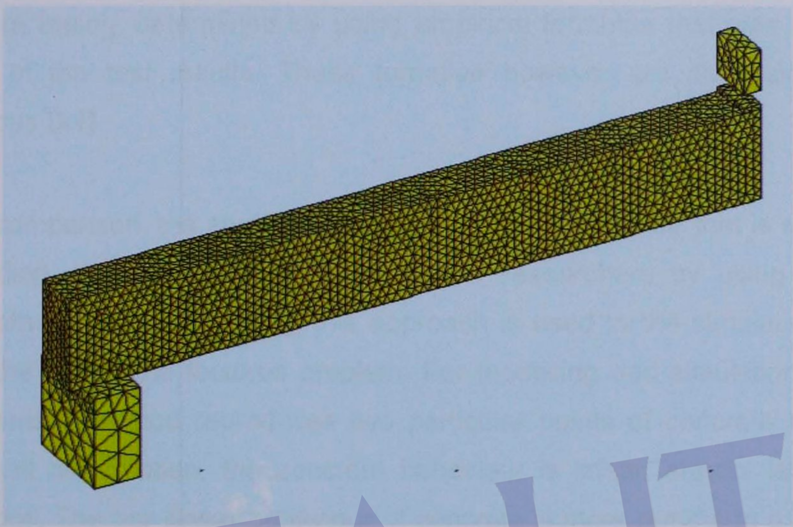

Figure 2.1: Example of three dimensional modelling of the beam and the impact block with different size mesh.

Some researchers such as **[14]**, **[15]**, **[16]**, and **[17]** have already simulated impacts on concrete structures, but commonly the models are not validated through simple tests. However, **[2]**, **[18]**, and **[19]** have succeeded in both of the experimental and simulation but the models of reinforced concrete structure are in small parametric dimension. In fact, the study of reinforced concrete structure under large mass low velocity impact using the computational technique of finite element methods has been done by **[20]**. In this study, the solution has been developed based on the combination of continuum and discontinuum method, to permit the simulation of impact loaded reinforced concrete beams. In the impact structure problem, most of the finite element modelling and simulation is performed by means of implicit transient analysis of the three-dimensional structure **[3]**, **[4]**, **[21]**, and **[22]**. In this case, the finite element analysis is based on the consistent tangents and the Newton-Raphson approach is adapted to solve the non-linear problems. The Newmark's time integration method is also used for transient dynamic analysis. For the discretization of reinforced concrete structures, solid element are used which adopts the linear interpolation function for displacement. Its reinforced concrete model accounts for cracking in tension and crushing in compression **[3]**. It is applied to the three-dimensional solid element in which the reinforcing rebars are included. It is allowed for considering the reinforcing rebars, modelled as unaxial structure with arbitrary orientation. Plastic behaviour and creep are considered in the reinforcing rebars. Besides, the amount of reinforcement is defined by specifying a volume ratio and the orientation angles of the rebars. During the simulation, the projectile is assumed to be non-deformable **[3]**. The local impact effects on concrete by the rigid projectile are mainly determined by using empirical formulae that was develop by data-fitting of the test results. These formulae however are dimensionally non-homogeneous **[21]**.

As comparison, the study of reinforced concrete structure that is subjected to impact loading also was performed by certain researchers by using a discrete element method. In **[18]** and **[22]**, this approach is used in the simulation study to overcome the brittle and factures problem. For modelling and simulation purposes, discrete element method reproduces two particular points of concrete behaviours. For the small deformation, the concrete behaviour is linear, elastic, isotropic and homogeneous. The non-linear behaviour of concrete is more remote to a nearly non-porous medium than to a granular material. In **[22],** the modelling and simulation procedure for missile impact on a concrete slab stated that this method does not rely on any assumptions on where and how a crack or several cracks occur and propagate, as the medium is naturally discontinuous and is very well adapted to the dynamic problem, when a transitioning from the solid state to a granular flow regime. However, concrete is known as a continuum medium of solid, thus finite element method is particularly a compatible approach for the impact-concrete interaction.

A large variety of models have been proposed in the last three decades to characterise the stress-strain behaviour of reinforced concrete beams and slabs. All these models have certain inherent advantages and disadvantages that totally depend on their particular application to a large extent. A perfect plastic model is often used to account for the plastic flow of concrete before crushing. The description of such a model requires the yield criterion and a flow rule for the direction of plastic deformation rate vector **[19]**. Frequently in finite element modelling, concrete beams and slabs are modelled as solid elements while reinforcement bar as lines. In the three-dimensional approach, solid, surface and line elements are formed by nodes. It will be conducted by defining the structured or unstructured element, depending on the form of structure's complexity. For certain concrete beams and slabs modelling, **[3]** used the four layers concept to model a reinforced concrete structure which consists of solid concrete, top and bottom reinforced and concrete cover, refer to Figure 2.2. The outer layers are the flexural reinforcing rebars and the shear reinforcing bars. The layer thickness is determined such that the centre of gravity of the flexural reinforcing rebars is situated in the middle of the layers.

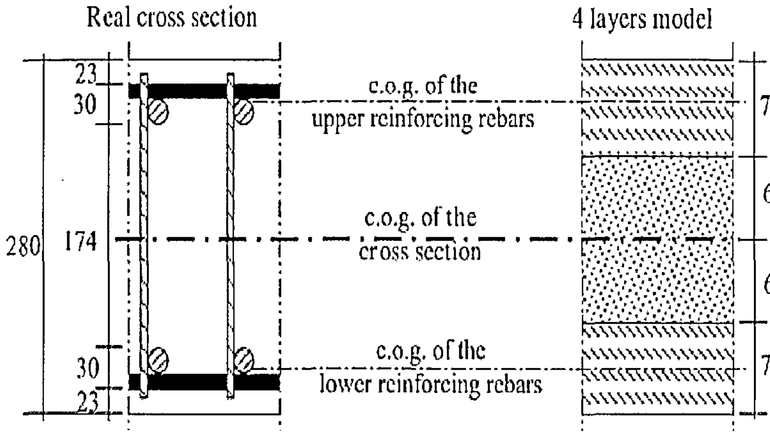

Figure 2.2: Cross section of the reinforced concrete structure with layers of the concrete.

In the two central layers, only shear reinforcing rebars are modelled. Their volume ratio is the same as in the real structure. The beams or slabs are discretized by means of cubic elements **[3]**. This approach is directly akin to that of the principle of slab modelling technique which was introduced by Dotroppe (1973), who utilised a layered finite element procedure, in which concrete structure elements were divided into layers to account for the progressive cracking through the slab thickness. For the reinforcing bars, the study in **[19]** represented the concrete and the reinforcement as a single element. A perfect bondage is assumed between the reinforcement and the surrounding concrete. Each set of reinforcing bar is smeared as a two-dimensional membrane of equivalent thickness. The layer is assumed to resist only the axial stress in the direction of the bars. **[18]** also used the same technique where the reinforcement is introduced in the model as lines of elements placed adjacent each other. The diameter of the elements is that of the real reinforcement and the local behaviour is considered as elastic, perfectly plastic.

In view of the reinforced concrete properties, **[1]** stated that the finite element modelling for solid concrete is generally based on a phenomenological behaviour under the macroscopic level where the concrete is subjected to impact loading. For this purpose, **[9]** has developed a simple elasto-plastic of finite element model that is subjected to a lateral impact loading. As some authors **[14, 23, 24]** mentioned that the reinforcement is introduced in the model as lines of elements placed adjacent to each other. The diameter of the elements is about the same size of the real reinforcement bars. On the other hand, **[19]** assumes that the linear elasticity is used for parts recoverable of the strain, and a plasticity approach is employed for the irrecoverable part of deformation. Note that the number of elements used in a model can greatly affect the accuracy of the solutions. In general, as the number of elements is increased, the accuracy of the model increases as well. As multiple models are created with an increasingly finer mesh, the results should converge to the correct numerical solution such that a significant increase in the number of elements produces an insignificant change in a particular response quantity. Another aspect that should be well considered is the boundary conditions and materials.

1.1 Impact Loading and The Damages

The simple terminology of impact in engineering is referred to as the dynamic effect on a structure, either moving or at rest of a forcible momentary contact of another moving body. Impact loads yield in shock waves, propagating through the elements with possible severe aftermath. When a projectile hits the material, a compressive wave is initiated by the impact. This compressive wave runs through the material to a free edge. The wave is reflected at that point and is transformed into tensile waves that propagate in the opposite direction. The general problem of this impact is extremely complex as it involves large displacements, material non-linearity, elastic and plastic instability, post-buckling strength, coulomb friction and material behaviour under high strain rates **[25]**. Impact loading can be classified up to several specific factors such as velocity, impactor mass and angle of obliquity **[7, 8, 26]**. Hard impact of concrete is characterised by a sharp peaked force per time relationship (1 to 3×10^{-3} seconds), regardless of the approach velocity **[27]**. This can lead to spalling, concrete plug formation, back face scabbing and the limiting completion of perforation for both reinforced concrete and pre-stressed concrete structures. In contrast, **[28]** recognized the low velocity impact as impact velocities in range 2.5m/s to 4.0m/s with weight capacity around 2.0kg. Consequently, the impact creates energy of a 21.0Joules, which is able to create the cracking which is then followed by the localized crushing, shear failure and finally breakage. However, **[29]** categorized the impact into velocity and failure mode which abbreviated from Zukas's theory. At velocities below 228m/s, the load-carrying behaviour of the entire structure is activated. In the medium velocities, which ranged between 500 and 1200m/s of impact, principally leads to local effects and higher velocities of the projectile and causing explosive vaporization of the materials.

Kennedy (1976), Bangash (1993), Williams (1994), dan Carbett (1996), Q. M. Li (2005) and other researches have described several phenomena associated with local impact effects on concrete targets, including penetration, cone cracking and plugging, spalling and scabbing, perforation and structure deformation **[30]**. Ever since, the understanding of concrete damages is pivotal to avoid disorganizing of terminology. Therefore, a standardized description of the different modes of damage caused by the impact loading is crucial to allow accurate comparisons among these various experiments. Brown and Perry **[27]** defined the following modes of concrete damages. Spalling is crater damage on the struck face while scabbing, fracturing and expulsion of concrete are often at high velocities, could form at the face opposite the struck face. In many circumstances, scabbing may occur before plug formation or as a result of plug movement. Perforation occurs when the missile passes completely through the slab whereas a concrete or shear plug is formed by an inclined cracking through thickness and is often in the form of a conical frustum. Figure 2.3 shows the local and overall impact phenomena due to impact.

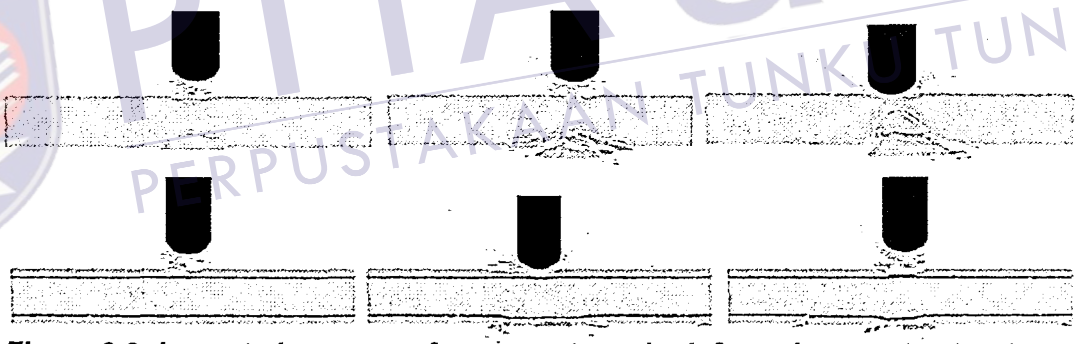

Figure 2.3: Impact phenomena for concrete and reinforced concrete structures, spallation on impact face, scabbing on back face and perforation.

Furthermore, **[31]** defined spallation as the ejection of a target material from the proximal face of the impacted structural target and it's controlled by the dynamic tensile behaviour of the concrete and it has been recognized as one of the main mechanisms of dynamic fracture of concrete. Meanwhile, **[5]** defined scabbing as the ejection of material from the back face of the impacted structural element placed opposite of the face of impact and it's produced by the reflection of shock waves on the rear face of the concrete structure. When a projectile hits the target, a compressive wave is initiated by the impact and it runs through the material to a free edge. In the midst of that, contact is assumed to be of no friction and no plastic strain appeared in the support, therefore, the behaviour is considered plastic **[25]**. The wave is reflected instantly and transforms into a tensile wave that propagates in the opposite direction **[27, 29]**. Generally, the area of scabbing will be much deeper than the spall area, but not so large. Once scabbing begins, the depth of penetration will increase rapidly, normally provoking a concrete plug to be formed by an inclined cracking. However, scabbing may occur even before, or as a result of, the movement of the concrete plug. Apart from the major damage caused at the point of contact during the hard impact, radial cracks which are spreading from penetration crater are usually formed on the back surface **[27]**.

The interaction between both impact body and the reinforced concrete structure has been related to a number of factors including relative masses, velocities, contact zone stiffness, frequency of loading, precision of impact, and the area of local energy absorbed **[32]**. Similarly, **[29]** described that the form and degree of impact damage is heavily influenced by the ratio of concrete thickness to the impactor diameter. Smaller ratio tends to cause scabbing and concrete plug formation. Impact will occur over a relatively large area of concrete for even lower values of ratio and behaviour will be dominated by the global flexural response of the slab although scabbing is still possible. Impactor shape does as well affect the kind of failure and the results for a pipe-shaped projectile have been discussed by **[33]**. Other factor influencing impact damage includes the deformability of the projectile, the velocity of impact, the relative characteristics of the target and missile and also the severity of impact **[34]**. Relatively low contact velocities with small missile mass will lead to small contact forces and exercise the structure in elastic. This type of impact does not generally cause any perceptible damage to the target. In fact, time histories of impact loads and ratio of absorbed energy by reinforced concrete play a crucial role **[16]**. On the other hand, **[7]** was the one who discovered that an oblique impact has an influence over the failure pattern where at a low impact velocity, the projectile is embedded but it can only penetrate one third in depth and then it ricocheted. Figure 2.4 shows how the oblique impact has an effect in the concrete damage.

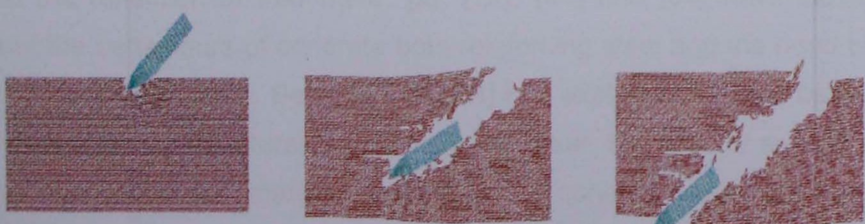

Figure 2.4: The effect of oblique impact on the concrete damage.

Reinforced concrete structures under impact loading shows the diverse behaviour from static loading. The effects of impact velocity towards the concrete damage can be understood by following the impact damage chronological as described by **[27]**. As the impact velocity increases, spalling in the form of crater with an area larger than the cross-sectional area of the impactor, may occur. Further increase of the missile velocity will result in the penetration with a depth greater than the depth of the spall crater and a cylindrical penetration hole larger than the diameter of the impactor. Some plastic deformation occurs within this increased velocity range, but the initial kinetic energy of the impactor is still recovered to a large extent during the rebound of the impactor. Up to this stage, where target penetration occurs, the concrete structure as a whole can be treated as an elastic for purpose of analysis. However, penetration of the target introduces predominantly an inelastic behaviour. A further increase in impactor velocity may produce cracking in the concrete on the back face of the target, followed by the expulsion of concrete from the back surface (scabbing), initiated by the reflected tensile wave effect.

1.2 Reinforced Concrete Beam and Crack Behaviour

Reinforced concrete has become one of the most important building materials and is widely used in many types of engineering structures such as beam, column and slab. Its economy, efficiency, strength and stiffness of this reinforced concrete, make it an attractive material for a wide range of structural applications. The application for the reinforced concrete beam is used typically to support floors, walls, decks and roofs. Concrete is known by nature a brittle material that performs well when in compression but is considerably less effective when in tension. Thus, reinforcement in concrete is utilised to absorb these tensile forces so that the cracking which is inevitable in all high-strength concretes does not weaken the structure. However, it was found that the economically reinforced concrete structures could fail by the yielding of the steel and the crushing of the concrete in the form of damage that is roughly similar under either static loading or impact. In dynamic problems, in particular impact load, concrete structures are failure due to the wave energy and the reflection of that wave. **[2]**, **[19]**, **[30]** and **[34]** have explained in details about the behaviours of concrete both reinforcing steel and the bond between reinforcing steel and concrete. Besides that, **[34]** has explained that the behaviour of this reinforced concrete structures is distinctly nonlinear, because of several factors. The factors are nonlinear material behaviour of concrete and steel and their interaction through bond and dowel action, cracking of concrete, and time dependent effects such as creep, shrinkage, temperature and load history.

Concrete is a common material for protective structures to resist any impacts and explosive loads. Concrete exhibits a large number of micro-cracks especially at the interface between coarser aggregate and mortar, even before it is subjected to any load. The response of a structure under load depends to a large extent on the stress-strain relation of the constituent materials and the magnitude of stress. Since concrete is used mostly in compression, the strain-stress relation in compression is of primary interest. The concrete stress-strain relation exhibits the response of the linear elastic to about 28% of the compressive strength. This is tailed by the gradual softening of the concrete compressive strength, when the material stiffness drops to nil. The softening of the compressive strength of the concrete stress-strain relation fails when crushing takes place. The relative weakness of concrete in tension and the yielding cracking is a fundamental factor affecting the non-linear behaviour of the reinforced concrete structures. It is assumed that when concrete is subjected to a tensile stress it behaves like an elastic-brittle material **[35]**. After the first crack has occurred, the concrete becomes orthotropic with the material axes oriented along the direction of cracking. According to **[35]**, the response of concrete under tensile stresses is assumed to be linear elastic until the fracture surface is reached. Figure 2.5 illustrates the bond interaction between concrete and reinforcement.

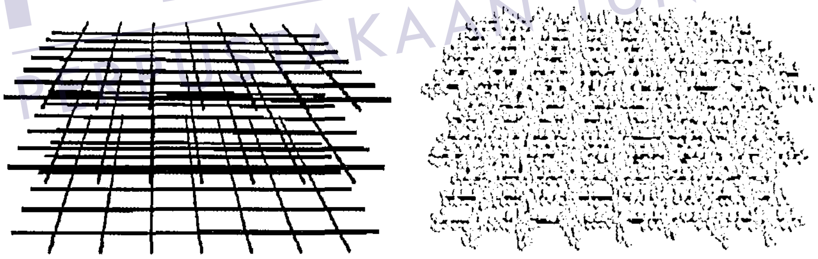

Figure 2.5: Bonding between concrete and reinforcing

The properties of reinforcing steel, unlike concrete, are generally not dependent on the environmental condition or time. Thus, the specification of a single stress-strain relation is sufficient to define the material properties needed in the analysis of reinforced concrete structures. Besides reinforcing steel bars of the elasto-plastic constitutive law, many investigations have already considered various constitutive laws including the strain rate's influence on the material properties **[1]**, and **[36]**. When the material is subjected to a short-term dynamic load, its stress-strain relationship determines the value of the strain and assumes the change to be inversely proportional. Typical stress-strain curves for reinforcing steel bars that are used in the concrete construction are attained from the coupon tests of bars loaded monotonically in tension. For all practical purposes, steel exhibits the same stress-strain curve in compression as in tension. The steel stress-strain relation exhibits an initial linear elastic portion, a yield plateau, a strain-hardening range in which stress again increases with strain and, finally, the range when the stress drops off when the fractures occur. The extent of the yield plateau is a function of the tensile strength of steel. High strength and high-carbon steels generally have a much shorter yield plateau than the relatively low-strength low carbon steels. Steel reinforcing bars used in the reinforced concrete structures are usually round with protrusions (ribs or lugs). These protrusions are accountable for the better bond characteristic between the reinforcing bars and the surrounding concrete. Steel bars have an elasto-plastic behaviour, as defined by its yield strength with a typical elasticity modulus of 190GPa. In this model, the reinforcing bars are modelled as layers of equivalent thickness. Each reinforcing layer exhibits a uniaxial response, having strength and stiffness characteristic in the bar direction only **[37]**.

Bond is an interaction between reinforcing steel and surrounding concrete. The force transferred from steel to concrete can be attributed to three different phenomena, firstly is the chemical adhesion between mortar paste and bar surface, secondly, the friction and wedging action of small dislodged and particles between the bar and the surrounding concrete and thirdly, mechanical interaction between concrete and steel. The bond of plain bars derives primarily from the first two mechanisms, albeit there is some mechanical interlocking caused by the roughness of the bar surface. Deformed bars have better bondage than the plain bars because most of the steel force is transferred through the lugs to the concrete. Friction and chemical adhesion forces are however secondary, and tend to decrease as the reinforcing bars start to slip. In the simplified analysis of reinforced concrete, structures with a complete compatibility of strains between concrete and steel is usually assumed to posses a perfect bond. This assumption is realistic only in regions where negligible stress transfer between the two components takes place. In regions of high transfer along the interface between the reinforcing steel and the surrounding concrete such as near crack, the bond stress is related to the relative displacement between the reinforcing steel and concrete.

Many researchers have studied the crack behaviours of reinforced concrete structural subjected to impact loads. Abbas et al **[19]** have presented a nonlinear analysis of reinforced concrete targets under the impact loading which is modelled with a strain rate sensitive elasto visco-palstic two surface models. In this study, the model of the reinforced concrete structure due to impact loading is to predict the cracking within the concrete region as well as the yielding of the steel reinforcement bars. The crack behaviour is attained from the simulation with low-velocity impact when applied with 100kg and 8.9m/s of the mass and velocity of the impactor respectively. In addition, a point load of 300kN is also applied onto the upper surface of the beam concentrated at the tip of the beam. Then, this beam is supported by a pin type of support at the top and bottom of the end of the beams to prevent the beam from sliding down and lifting up. As the results, Figure 2.6 shows the propagation of crack in the beam.

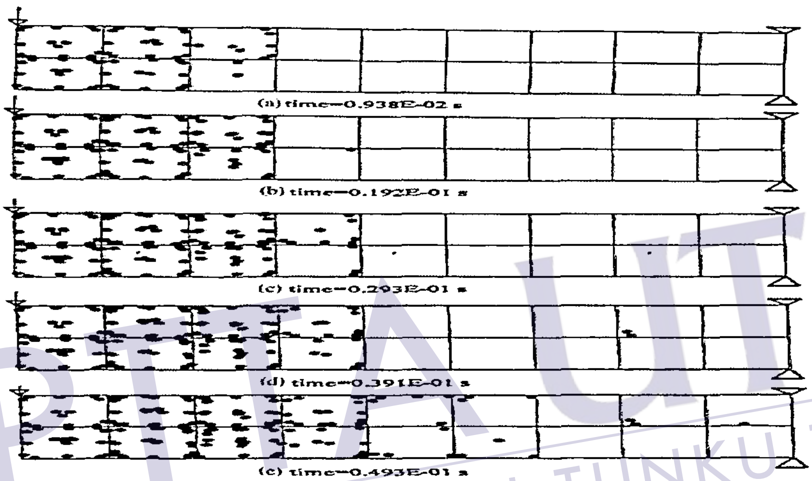

Figure 2.6: propagation of cracks in beam as obtained by Abbas et al.

Crack propagation obtained by Abbas's model in two-dimensional model is not exactly perfect when the region as a whole is taken into account. The crack propagation in this model is also unable to show the scabbing and spallation damage behaviour because of the cracks that happened at the whole vertical area of the impact area. According to Abbas's result, there are two aspects which consideration is compulsory in evaluating the crack propagation and the cracking pattern. Crack propagation in finite element analysis depends on the meshing size. A fine size of finite element mesh will give an accurate result of the crack behaviour. Since crack behaviour is fully dependent on particular timing, hence, the three-dimensional is absolutely required. Consequently, Thabet and Haldane **[38]** have modelled the finite element model at different time steps and fine mesh sizes as shown in Figure 2.7. The crack pattern obtained by Thabet and Haldane are reasonably similar to Abbas's model. However, the crack patterns in Thabet and Heldane model show that the crack also happens in the support region which does not occur in Abbas's model.

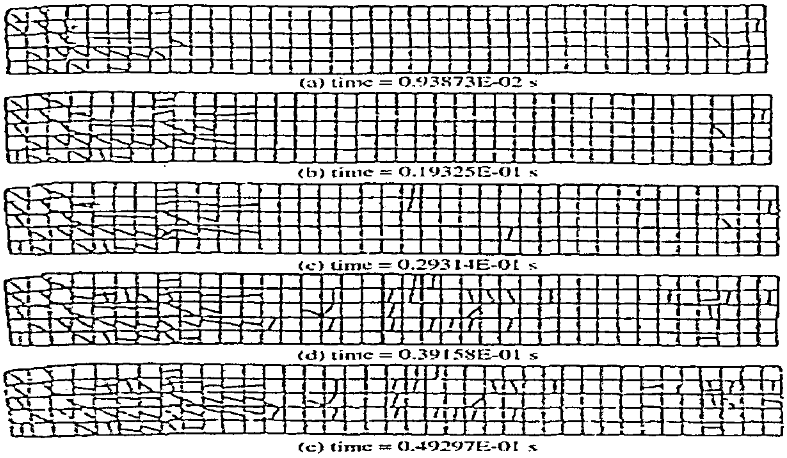

Figure 2.7: Predicted crack pattern for beam analysed by Thabet and Haldane

On the other hand, Kishi et al **[39]** have studied the behaviour of impact damage of reinforced concrete beams by comparing the shear and without shear rebars. In this study, simple support beams with 250mm of depth and 150 mm width is used, with the main rebar of diameters 13mm and 19mm. The main aim of this study is to investigate the elastic behaviour of the beam under low-velocity impact loads. As a result, the development of the crack pattern is sketched as shown in Figure 2.8. Based on this result, the crack pattern of the reinforced concrete beam under low-velocity impact is involved the scabbing crack at the bottom side of beam, spallation crack at the top area of the beam and shear cracks at the support area. The cracks are propagated from the mid span of the beam to the support point. The scabbing crack takes place first, followed by several diagonal cracks which developed the spallation cracks. At the final stage of the impact, the reinforced concrete beam is splitted into several parts around the support area due to further development of diagonal crack. It can be seen as well as that flexural crack is a factor that contributes to the scabbing crack.

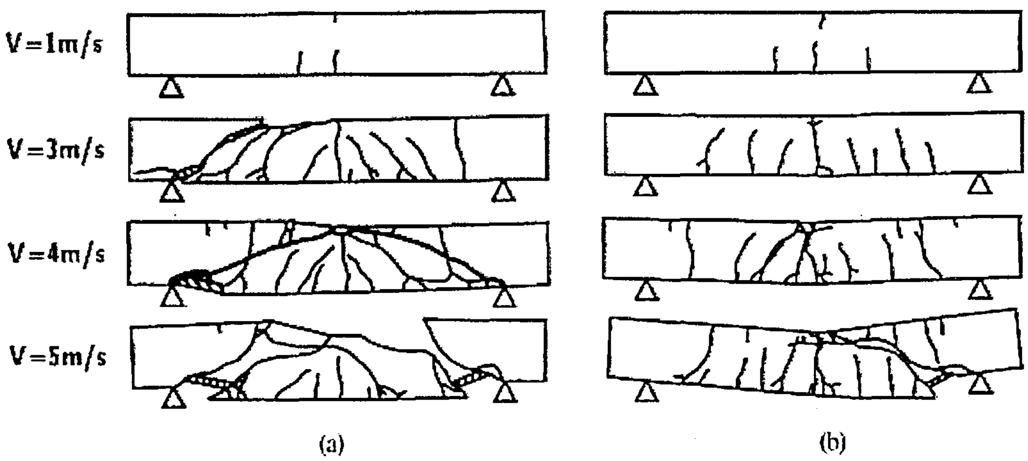

Figure 2.8: Crack pattern for beam with and without shear rebar sketched by Kishi et al

For three-dimensional model of reinforced concrete structures subjected to impact loads, A.T. Bere **[40]**, P. J. Thiele **[5]** and S. Zou **[41]** have studied this kind of impact problem using ELFEN software. A. T. Bere has modelled and simulated the reinforced concrete beam under a large mass low-velocity impact using 3100 mesh elements. It was discovered **[40]** that the cracks revealed on the concrete can be analysed according to the damage indicator, concrete facture and velocity vector of impact and wave energy. Hence, in this model, a rotating crack model is used for the representation of fracturing in the concrete **[5]**. P. J. Thiele continued the similar model with a low-velocity impact in various conditions like different support, thickness of impact plate and meshing size. In Thiele's model, the crack patterns are significantly influenced by the support conditions. Figure 2.9 shows the crack behaviour taken from the experimental result while Figure 2.10 and Figure 2.11 are crack patterns respectively from A. T. Bere and P. J. Thiele studies. Besides that, **[5]** also stated that the first region of crack appears in the vicinity of the impact with the cracks propagating from the near bottom edge of the concrete towards the centre of the beam at an angle of approximately 45 degree. In addition, it can be concluded that the final crack pattern contains three main regions of cracking. The first one is directly beneath the impact zone and in a cone-like shape. The second is at the bottom of the beam between the centre and quarter beam length away from the centre. The final region is initiated on the top surface of the concrete beam between the support and the quarter beam length from the support toward the centre **[5]**.

Figure 2.9: Crack pattern by laboratory experimental

Figure 2.10: Crack pattern by Bere's model

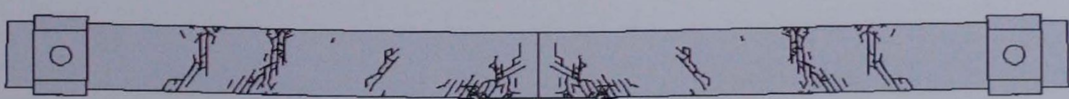

Figure 2.11: Final crack pattern by Thiele's model

Chapter 3

Methodology

3.0 Methodology

Flow charts as shown in Figures 3.1 and 3.2 describe the simple route of the study of the finite element modelling of reinforced concrete structures under impact loading. The study is divided into three main categories including preliminary studies of reinforced concrete under impact, modelling and simulation, and results analysis

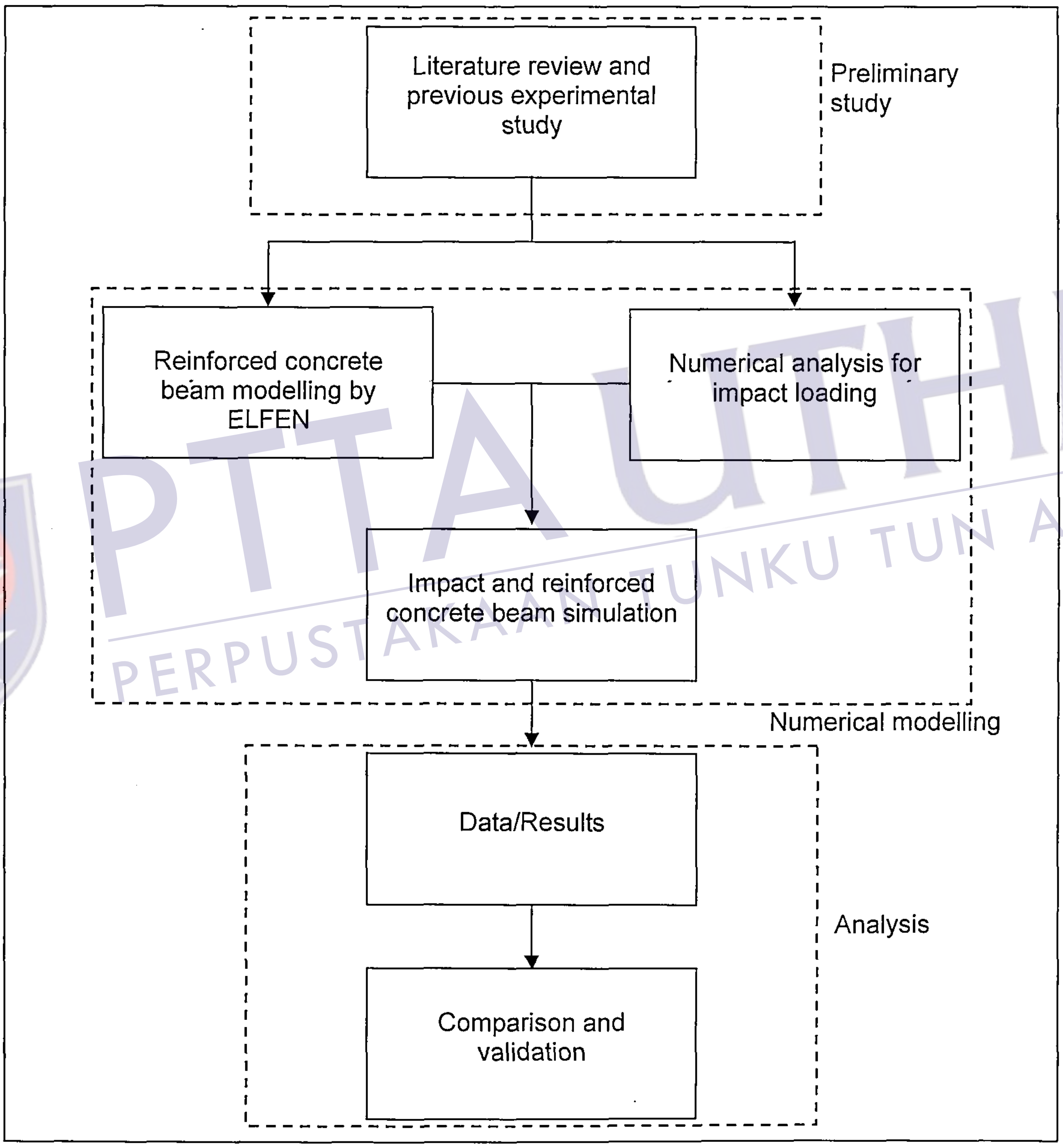

Figure 3.1: Flow chart for the whole process of this study

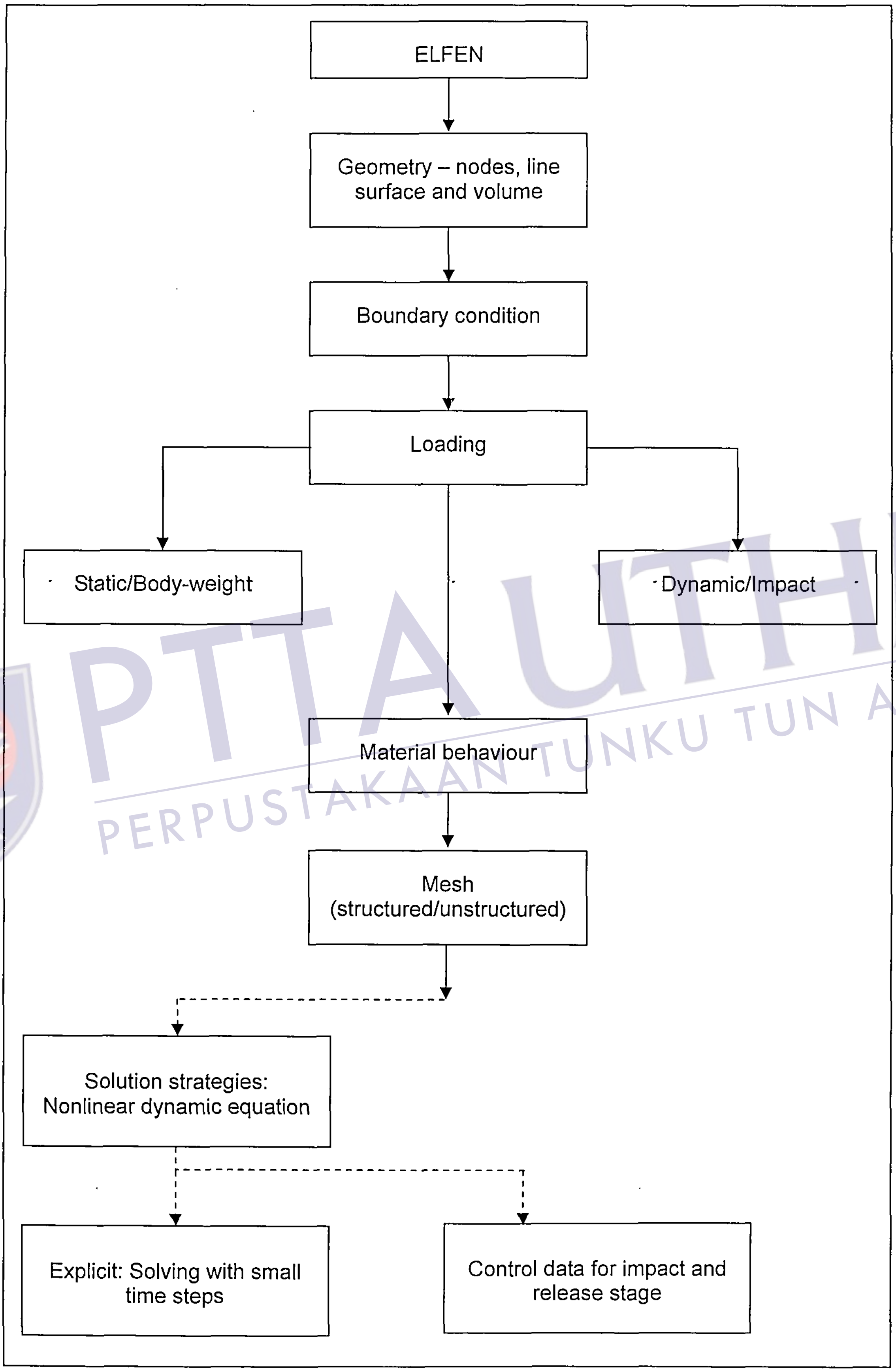

Figure 3.2: Flow chart for beam modelling in ELFEN

3.1 Finite Element Modelling by ELFEN

ELFEN is a two/three dimensional numerical modelling package that incorporates all the latest finite element and discrete element analysis to enable it to solve a wide range of engineering problems **[38]**. ELFEN has been developed in Swansea with a generally purpose of finite element and discrete element system incorporating pre-processing facilities for model generation, material database and import facilities. Besides these, this software provides implicit or explicit analysis capabilities and post processing facilities for assessment for results. ELFEN has been used for a wide variety of application in diverse engineering disciplines including the seismic analysis of reinforced concrete buildings and failure analysis of composite shell structures. For material problems in engineering, ELFEN is also utilised to analyse impact of structures with brittles and ductile materials. Therefore, ELFEN is recognized as one of the most suitable programmes to study about these impact problems. As one of the advanced tools in finite element method, ELFEN specifically analyses a wide range of continuous and discontinuous engineering applications. The examples of continuous and discontinuous engineering application are linear static, transient dynamic, non-linear material such as concrete and geometry non-linearity. Contact and impact are also included in this engineering application.

Finite element analysis was first developed in 1943 as a mathematical solution to obtain approximate solutions to a torque problem. Since the rapid growth of computer technology, the finite element method has been developed to an incredible precision. The finite element method consists of a numerical model of a structure that is stressed. The current version of finite element analysis is able to solve linear static and dynamic structural and thermal analysis problems. That is why, ELFEN, as one of finite element analysis tools, has been developed to analyse the mechanical problems in implicit and explicit process control of procedures. ELFEN also provides the thermal analysis in the implicit approach and thermo-mechanical coupling. In the finite element modelling and simulation, there are a number of solution procedure steps: specify geometry, apply loading, apply boundary conditions and other constraints, specify material properties, select element type, meshing, solution generation, post-processing, mesh refinement and interpretation of results **[5]**.

Reference

[1] Y.S. Tai, C.C. Tang (2006). "Numerical Simulation: The Dynamic Behaviour of Reinforced Concrete Plates under Normal Impact". Theoretical and Applied Fracture Mechanic (Vol.45), 117-127, Elsevier.

[2] M. Zineddin, T. Krauthammer (2007). "Dynamic Response and Behaviour of Reinforced Concrete Slabs under Impact Loading". International Journal of Impact Engineering (Vol.34), 1517-1534, Elsevier.

[3] F. Delhomme, M. Mommessin, J.P Mougin, and P. Perrotion (2007). "Simulation of a Block Impacting a Reinforced Concrete Slab with a Finite Element Model and Mass Spring System". Engineering Structures (Vol.29), 2844-2852, Elsevier.

[4] B.R. Philippe, T. Yehya, L. Daudeville, and J. Mazars (2003). "Finite Element Modelling of Concrete Protection structures Submitted to Rock Impacts". 16th ASCE Engineering Mechanics Conference, University of Washington.

[5] P.J. Thiele (2006). "Behaviour of Reinforced Concrete Beam Under Low Velocity Impact Load'. Mres Thesis, Swansea University.

[6] J.P.Mougin, P. Perrotin, and M. Mommessin (2003). "Rock Fall Impact on Reinforced Concrete Slab: an Experimental approach". International Journal of Impact Engineering (Vol.31), 169-183, Elsevier.

[7] T.L. Teng, T.A. Chu, F.A. Chang,. and H.S. Chin (2004). "Simulation Model of Impact on Concrete Reinforced Concrete". Cement and Concrete Research (Vol.34), 2067-2077, Pergamon.

[9] A.N. Dancygier, D.Z. Yankelevsky (2000). "Effect of Reinforced Concrete Properties on Resistance to Hard Projectile Impact". ACI Structure Journal (Vol.96), 259-267.

[9] T. Ando, N. Kishi, H. Mikami (2007). "Applicability of FEA on RC Columns Under Lateral Impact Loading ". Proceeding Paper, 3rd International Conference on Concrete Under Severe Condition, 581-588.

[10] A.C. Miranda, M.A. Meggiolaro, J.T.P. Castro, and L.F. Martha (2003). "Finite Element Modelling of Crack Bifurcation."Computational Fluid and Solid Mechanics, Rie de Janeiro.

[11] Y.G. Du, A.H.C. Chan, S. Williamson and L.A. Clark (1999). "FEM Analysis of Concrete Cracking." Computational Modelling of Concrete Structures, 481-490, Balkema.

[12] K. M. Lynn, D. Isobe (2006). "Finite Element Code for Impact Collapse Problems of Structures". International Journal for Numerical Method in Engineering (Vol.69), 2538-2563, Wiley InterScience.

[13] W.F Chen (1994). "Constitutive Equations for Engineering Material'. Plasticity and Modelling (Vol.2), Elsevier.

[14] K. Meguro, M. Hakuno (1989). "Fracture Analyses of Concrete Structures by the Modified Distinct Element Method". Structural Engineering (Vol.2), 283-294, Elsevier.

[15] N. Kusano, T. Aoyagi, J. Aizawa, H. Ueno, H. Morikawa, and N. Kobayashi (1992). "Impulsive Local Damage Analyses of Concrete Structure by the Distinct Element Method". Nuclear Engineering and Design (Vol.138), 105-110, Elsevier.

[16] Y. Sawamoto, H. Tsubota, Y. Kasai, N. Koshiba, and H. Morikawa (1998)."Analytical Studies on Local Damage to Reinforced Concrete Structures under Impact Loading". Nuclear Engineering and Design (Vol.179), 157-177, Elsevier.

[17] F. Camborde, F.C. Mariotti, and F. V. Donze (2000). "Numerical Study of Rock and Concrete Behaviour by Discrete Element Modelling". Computers and

Geotechnics (Vol.27), 225-247, Elsevier.
[18] L. Dadville, F.V. Donze, and J. Mazars (2005). "Impacts on Concrete Structures: From the Local Analysis to the Structural Behaviour". VIII International Conference on Computational Plasticity, Barcelona.
[19] H. Abbas, N. K Gupta, and M. Alam (2004). "Nonlinear Response of Concrete Beams and Plates under Impact Loading". International Journal of Impact Engineering (Vol.30), 1039-1053, Elsevier.
[20] I. May, R. Owen, Y. Feng, Y. Chen, and P.Thiele (2006). "Analysis and Testing of Reinforced Concrete Beam under Large Mass Low Velocity Impacts". Computational Modelling in Finite Element, Swansea.
[21] K. Xu, Y. Lu (2005). "Numerical Simulation Study of Spallation in Reinforced Concrete Plates Subjected to Blast Loading". Computer and Structures (Vol.84), 431-438, Elsevier
[22] W.J. Shiu, F. Donze, and L. Daudeville (2005). "Missile Impact on a Concrete Slab: a 3D Study" *Laboratoire Sols, Solides, Structures: Wshiu Annual Report*, Grenoble (France).
[23] S.A. Magnier, and F.V. Donze (1998). "Numerical Simulations of Impacts Using a Discrete Element Method". Mechanics of Cohesive-Frictional Materials (Vol.3), 257-276.
[24] H. Masuya, Y. Kajikawa, and Y. Nakata (1996). "Application of the Distinct Element
Method to the Analysis of the Concrete Members under Impact". Nuclear Engineering and Design (Vol.150), 367-377.
[25] P. E Wright (2008). "Introduction to Impact Loading". PDH Courses164.
[26] V. Philippe, B. Ludovic, G. Laurent, and L. Jean (2007). "Scale Effects on the Response of Composite Structures Under Impact Loading". Engineering Fracture Mechanics (Vol.75), 2725-2736, Elsevier.
[27] S.H. Perry, G. Dinic, and P.H. Bischoff (1989). "Formation of Full Depth Cracks in Concrete Slabs Subjected to Hard Impact". Structures under Shock and Impact, Elsevier.
[28] C.S. Juan, K.V. Uday, and U. Nasim (2006). "Low Velocity Impact Response of Autoclaved aerated Concrete". Composite Structures (Vol.80), 621-630, Elsevier.
[29] B. Christian, K. Manfred, and K. Adrea (2006). "Perforation Resistance of High-Strength Concrete Panels". ACI Structural Journal.
[30] Q.M. Li, S.R. Reid, and A.M. Ahamad Zaidi (2005). "Critical Impact Energies for Scabbing and Perforation of Concrete Target". Nuclear Engineering and Design (Vol.236), 1140-1148, Elsevier.
[31] H. Wu, Q. Zhang, F. Hung, and Q. Jin (2005). "Experimental and Numerical Investigations on the Dynamic Tensile Strength of Concrete". International Journal of Impact Engineering.
[32] A.M. Remennokov, and S. Kaewunruen (2006). "" Impact Resistance of Reinforced Concrete: Experimental Studies and Design Considerations". 19th Australasian Conference on the Mechanics of Structures and Materials.
[33] S.H. Perry (1989). "Assessment of Impact damage Caused by Dropped Objects on Concrete Offshore Structures". HMSO 79-151, London.
[34] Q.M. Li, X.W. Chen (2003). "Dimensionless Formulae for Penetration Depth of Concrete Target Impacted by a Non-Deformable Projectile". Journal of Impact Engineering (Vol.28), 93-116, Pergamon.
[35] H.G. Kwak, F.C. Filip (1190). "Finite Element Analysis of Reinforced Concrete Structures under Monotonic Loads". Structures Engineering Mechanics and Materials, California.
[36] A.J.M. Ferreira, P.P. Camanho, and A.T. Fernandes (2001). "Modelling of Concrete Beam Reinforced with Re-Bars". Composite Structures (Vol.53), 107-116, Elseveir.

[37] H.M. Gomes, A.M. Awruch (2001). "Some Aspect on Three-Dimensional Numerical Modelling of Reinforced Concrete Beam Structures Using the Finite Element Method". Advanced in Engineering Software (Vol.32), 257-277, Elsevier.

[38] A. Thabet, D. Haldane (2000). "Three-Dimensional Simulation of Nonlinear Response of Reinforced Concrete Member Subjected to Impact Loading". ACI Struct J (Vol.91), 689-701.

[39] N. Kishi, H. Mikami, K.G. Matsuoka, and T. Andi (2002). "Impact Behaviour of Shear Failure Type RC Beam Without Shear Rebar". International Journal of Impact Engineering (Vol.27), 955-968.

[40] A.T. Bere (2004). "Computational Modelling of Large-Scale Reinforced Concrete Structure Subject To Dynamic Loading".), Phd Thesis, Swansea University.

[41] S. Zou (2007). "Behaviour of RC Slabs Under Low-Velocity Impact Loads". MSc Dissertation, Swansea University