FINITE ELEMENT SIMULATION OF REINFORCED CONCRETE SLABS UNDER IMPACT LOADING

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ABSTRACT

In a few years ago, efforts for assessing and predicting the behaviour of concrete structures subjected to impact loads have been hampered by lack of adequate computational procedure and unavailability of good quality experimental results. Furthermore, computer software was also not yet developed up to the standards of today. Nowadays, the numerical models for the impact load assessment are starting to become more accurate and reliable. Combined with modern computer hardware, the computational time for such an assessment has been reduced to a satisfactory level. In this study, an attempt has been made to examine the accuracy of modern software with regards to assessing the response of reinforced concrete slabs subjected to impact loading near the ultimate load ranges. The response such as Time-Impact force graph, damage wave propagation, failure process of steel reinforcement, effectiveness of mesh density, effect of projectile size and final crack pattern are verified against existing experimental results. It is shown that the present general purpose finite element software is able to simulate and predict the structural behaviour satisfactorily.

ABSTRAK

Beberapa tahun yang lepas, cara untuk menilai dan meramalkan kelakuan yang berlaku pada struktur akibat dari beban hentaman kurang dari segi prosedur penyelesaian mengunakan perisian komputer, laporan mengenai kajian yang tidak lengkap serta kekurangan keputusan secara eksperimen. Selain itu juga, perisian komputer pada masa dahulu tidak dibangunkan seperti kemajuan terkini. Dengan adanya kemajuan dalam bidang pengkomputeran kini, maka penilaian simulasi bagi model struktur yang menggunakan perisian komputer menjadi semakin tepat dan boleh dipercayai. Dengan kombinasi dengan perkakasan komputer yang moden, maka, masa untuk penilaian simulasi yang berbantukan komputer dapat dikurangkan ke tahap yang memuaskan. Dalam kajian ini, percubaan telah dilakukan untuk menyelidik ketepatan perisian moden mengenai penilaian kelakuan bagi konkrit bertetulang dengan dikenakan beban hentaman yang menyamai dengan julat beban muktamad. Kelakuan hasil kajian seperti graf Masa-Daya Hentaman, serakan gelombang kegagalan, proses kegagalan bagi besi tetulang, keberkesanan bagi ketumpatan jejaring yang berbeza, kesan saiz besi hentaman yang berbeza dan juga bentuk muktamad keretakan pada struktur ditentusahkan dengan perbandingan kepada kajian secara eksperimen. Ini menunjukkan bahawa perisian unsur terhingga yang digunakan berupaya untuk mensimulasikan dan meramalkan kelakuan struktur dengan memuaskan.

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***p*-**	Material Density
***V* -**	Volume
***F*-**	Force
M -	Mass
v -	Velocity
***E*-**	Stored internal energy
***i* -**	Initial condition
***f*-**	Final condition
***x* -**	Impulsive load
***F*-**	Impact load
***t*-**	Time
***k*-**	Contact parameter

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CHAPTER I

INTRODUCTION

1.1 An Overview of R.C Structures under impact loading

Impact or impulsive loading is the most important dynamic factors taht should be considered in designing critical structures such as defenses' military, nuclear plant shell and mountain area buildings. Unlike earthquake or vibration conditions, impact have multi-uniqueness characteristic which should be taken into account in design. The analysis and design of structures that are subjected to dynamic loading are often very complex. Such analyses are further complicated when working with non-elastic materials such as reinforced concrete. For non-linear material, conventional approach of structural analysis is not longer enough to define the real behaviour of concrete structure under extreme load. Therefore, the responses of concrete to transient dynamic loading have been explored extensively for both civil and military application. In term of impact loading, the understanding of the response of concrete to impact or explosive loading is essential to protect fortifications (Y.S. Tai et al., 2006). Impact load is the dynamic effect on structure, either moving or at rest of forcible momentary contact of another moving body. The mechanism of impact is usually caused by missile, vehicle crash or objects whose drop or beat in the structure surface. In structural engineering, impact loading mostly one of accountability subject for walls, beams and slabs both in steel and concrete.

Research in structural engineering in the last decade has increasingly focused on behaviour beyond the elastic range and conditions where dynamic response is encountered. Structural elements would subject to various loading conditions during their service life, and hence may initiate failure to the structure. One of the important loading type that a structural element may have to sustain is impact loading.

Reinforced concrete slabs are among the most common structural elements. In spite of the large number of slabs designed and built, the effect of their details on their behaviour under impact loads are always appreciated or properly taken into account (M. Zineddin et al., 2007). So that, there has been a growing interest in the past few decades among the engineering community to understand the response of 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 catastrophic and sudden structural failure. Reinforced concrete structures are often subjected to extreme dynamic loading conditions due to direct impact. The typical examples such as transportation structures subjected to vehicle crash impact, marine and offshore structures exposed to ice impact, protective structures subjected to projectile or aircraft impact, and structures sustaining shock and impact loads during explosions were listed by (M. Zineddin et al., 2007).

1.2 Problem Statement

During the impact loading process, the capability of concrete to take higher stress will increase due to the high strain rate; therefore, strain rate effects and local fracture phenomena have to be taken into account in the computational model or numerical simulation. Of particular relevance is the ability to predict the behaviour of the impacted structure within the nonlinear range, where wide cracking of the concrete can take place in conjunction with yielding of the steel reinforcement bars, resulting in mechanisms leading to scabbing, spallation, penetration and possibly even complete failure of the structure.

In a few years ago, the way to ensure that prediction of the response of such impacted structures, such as near ultimate load effects of scabbing, spallation and penetration, has been hampered both by a lack of adequate (computational solution procedures and the availability of good quality, comprehensively reported, experimental results). In addition to that, computers were not yet developed to the standards of today. The numerical simulations require a vast amount of computational power and can take a very long time to complete. According to the development of the computer program that is currently made in this field the numerical models are starting to become more and more accurate and reliable, as well as fairly quick to obtain.

1.3 Research Objectives

The objectives of the research are:

1) To investigate the failure mechanism of an R.C slabs under impact loading.

2) To propose a method for modelling and analysis of an R.C structure subjected to impact loading.

3) To determine the accuracy of result which can be expected from finite element analysis when simulating reinforced concrete slabs subjected to impact loads.

4) examine the effect of different non-linear material models which are available in the ABAQUS/Explicit material library on the dynamic response of an R.C slabs.

1.4 Scope of Research

This study involves the development of Finite Element model of a square **R**.C slab using ABAQUS software version 6.8-1, and analysis of the model under impact load. Effect of several non-linear concrete materials models was investigated. The model that resembles the test data was developed further to study the behaviour of **R**.C slab at near failure load.

1.5 Significant of This Research

Many existing building structures that are exposed to dynamic load are not designed to resist the load. Examples of such buildings include those near an airport which are exposed to vibration due to aircraft landing and takeoff, buildings at strong wind path which are subjected to repeated wind load and buildings near highway that are expose to vehicle collision load or impact load.

According to the above matters, the numerical simulation could be the one of quick tools to investigate the behaviour of the concrete structures subjected to the impact loads and buildings could be designed to resist this dynamic loading. Furthermore, special attention is given to the design of structures where the risk of impact is high or where structural failure as a result of impact could result in consequences disproportional to the severity of the impact. Being able to predict the response of such structures by numerical means is a distinct advantage as only that way a safe design can be guaranteed.

Analysis of these types of buildings can be performed numerically using existing software. Therefore, this study involves the development of Finite Element model of R.C slab using ABAQUS software. The slab is subjected to drop-weight impact loading. Based on the result that obtained in this research, it could give the better understanding on the failure mechanism of the concrete structures including the factors that affect the impact loading.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

In order to provide the fundamental understanding for the impact loading on reinforced concrete slab. Three main topics of literature review were divided in this particular Chapter. The topics that will be explained in the next following paragraphs are finite element modelling and simulation, impact loading and its effect, and reinforced concrete slab. The understandable knowledge to impact loading and reinforced concrete behaviour under this kind of loading is seriously essential before finite element modelling and simulation could be implemented.

In this Chapter, some of the previous research as well as the published works regarding the simulation of impact loading and experimental investigations were discussed. Therefore, it could achieve the aim of this Chapter to provide a background and supporting knowledge on the effects of impact loading on reinforced concrete.

2.1.1 Finite Element Modelling and Simulation

Over the past several decades, the finite element method has been widely employed for solving linear elastic and elastic- plastic failure problems, as well as has become 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 solution of a problem in continuum mechanics is approximated by the analysis of an assemblage of finite elements which are interconnected at finite number of nodal points and represent the solution of the problem (K.M. Lynn et al., 2006). Development in computational power and advances in finite element simulation have led to the establishment of sophisticated computer models that can simulate structural materials and members with a fair degree of accurateness. Concurrently, ABAQUS, ANSYS, LUSAS and other finite element software packages have made nonlinear finite element analysis a feasible tool for evaluating, designing, simulating and predicting many kinds of engineering problems.

Fundamentally, complex structures are divided into a large number of small elements during the finite element process, whose stress-strain relationships are more simply approximated. Then the conditions of dynamic quilibrium and the boundary conditions on each of the thousands of elements were enforced by the software computer program. This could allow the analyst to determine the displacements and stress associated with each element. Consequently, the behaviours and structure failures is easily to analyse in any kind problems of loads. The finite element method analysis of the reinforced concrete structure, typically applies the separation, combination or holistic mode formula to perform the modelling (W.F Chen, 1994). Since, under bearing external impact for short duration, the reinforcing bars and the concrete can be assumed to have a good bonding property, preventing the two materials from sliding. So that, (Y.S Tai et al., 2006) in 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. **Figure 2.1** shows the reinforced concrete slab and impact block which is create with different element mesh.

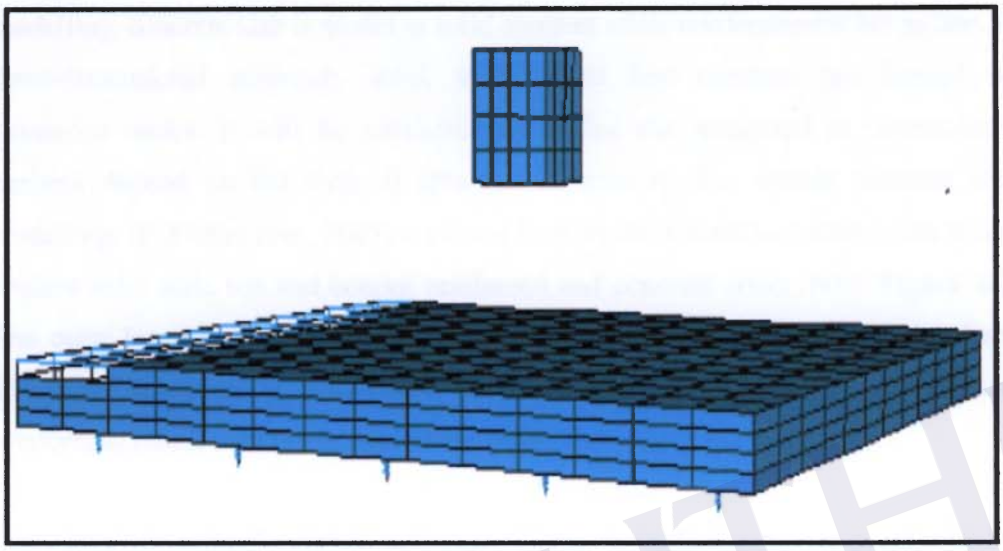

Figure 2.1: Example of three dimensional modelling of the slab and the impact block.

A number of researcher such as (K. Meguro et al., 1989; Kusano T et al., 1992; Y. Sawamoto et al., 1998; F. Camborde et al., 2000) have already simulated impacts on concrete structures, but usually the model are not validated through simple tests. However, (M. Zineddin et al., 2007), (L. Dadville et al., 2005) and (H. Abbas et al., 2004) have been success in both of experimental and simulation but the model of reinforced concrete is in small parametric dimension. Besides that, the study of reinforced concrete under large mass low velocity impact using computational technique of finite element method also have been done by (I. May et al., 2005). In this particular research, the solution have been cretaed based on combination of continuum or and discontinuum method to permit the simulation of impact loaded reinforced concrete slabs.

In the previous three decades, a great variety of models have been proposed to characterise the stress-strain behaviour of reinforced concrete slab. All these models have certain inherent advantages and disadvantage, which depend, to a large extent on their particular application. A perfect plasticity 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 (H. Abbas et al., 2004). Commonly in finite element modelling, concrete slab is model as solid element while reinforcement bar as line. In three-dimensional approach, solid, surface and line elements are formed by numerous nodes. It will be conducted by define the structured or unstructured element depend on the form of structure complexity. For certain concrete slab modelling, (F. Delhomme., 2007) was used four layers concept to model a slab which content solid slab, top and bottom reinforced and concrete cover, refer **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 gravity of the flexural reinforcing rebars is in the middle of the layer.

Only shear reinforcing rebars are modelled in the two central layers. Their volume ratio is the same as in the real structure. In order to comply, the slab is discretized by means of cubic elements (F. Delhomme., 2007). This approach directly similar with principle of slab modelling technique who are introduced by (Dotroppe et al., 1973) which used a layered finite element procedure in which slab elements were divided into layers to account for the progressive cracking through the slab thickness. For reinforcing bar, (H. Abbas et al., 2004) in his present study represented the concrete as well as the reinforcement with a single element. Perfect bond 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. (L. Dadville et al., 2005) also use the same technique where the reinforcement is introduced in the model as lines of elements placed next to each other, see **Figure 2.3.** The diameter of the elements is that of the real reinforcement and the local behaviour is considered as elastic, perfectly plastic.

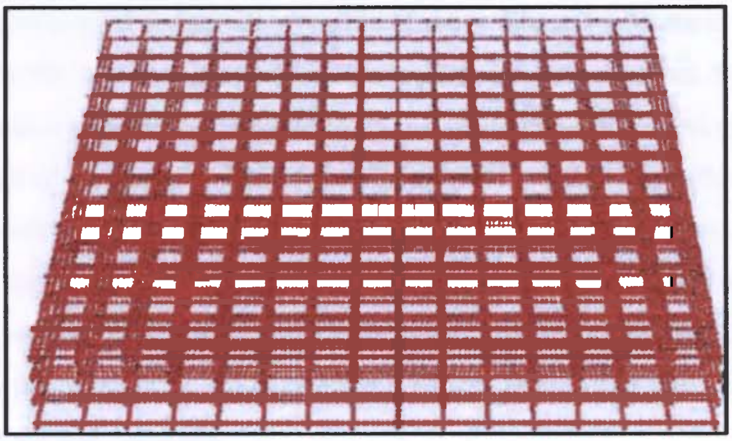

Figure 2.2: Cross section of the slab and four layers model.

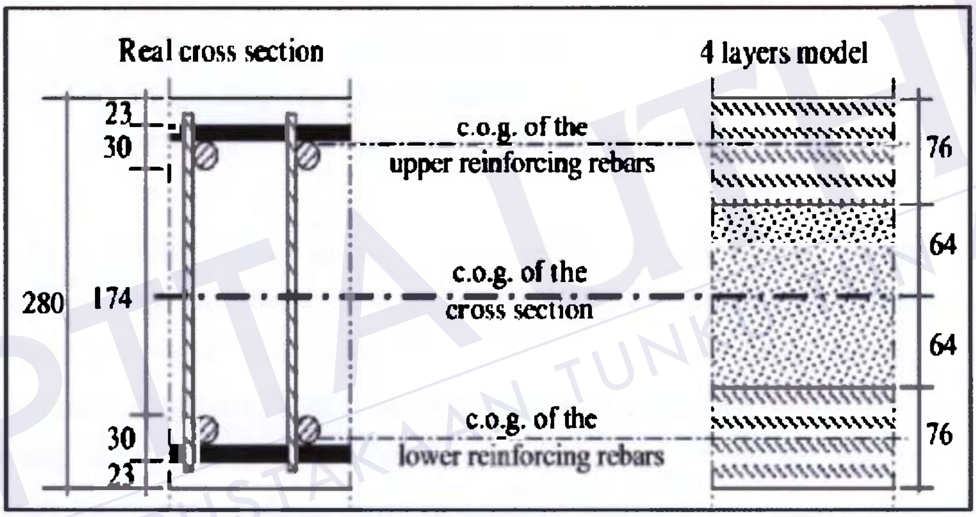

Figure 2.3: The four reinforcement layers of the concrete slab.

For the reinforced concrete properties matter, (Y.S. Tai et al., 2006) stated that finite element modeling for solid concrete is generally based on a phenomenological behaviour under the macroscopic level when the concrete is subjected to impact loading. (Ando et al., 2001) have developed a simple elasto-plastic finite element model subjected to lateral impact loading. As some authors (K. Meguro et al., 1989), (S.A. Magnier et al., 1998) and (H. Masuya et al., 1998), the reinforcement is introduced in the model as lines of elements placed next to each other. The diameter of the elements is about the same size of the real reinforcement bars. On the other hand, (H. Abbas et al., 2004) in the modelling aspect supposed that linear elasticity is used for part recoverable of the strain, and a plasticity approach is employed for the irrecoverable part of deformation. In another aspect, the number of elements used in a model can greatly affect the accuracy of the solution. In general, as the number of elements, or the fineness of the mesh, 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 careful into the accqunt is boundary layers and materials.

2.1.2 Impact Loading and The Damages

A general case of impact - involves large displacements, material non-linearity, elastic and plastic instability, post-buckling strength, coulomb friction, and material behaviour under high strain rate. On the other hand, the impact in engineering perspective is referred as the dynamic effect on a structure, either moving or at rest of a forcible momentary contact of another moving body. Impact loads result in shock waves propagating through the elements with possible serious consequences. (M. Zineddin et al., 2007) and other researcher described several phenomena associated with local impact effects on concrete targets, including penetration, cone cracking and plugging, spalling and scabbing, perforation and structure deformation.

(Faham, 2008) mentioned the problems with impact loads usually involve all three fundamental approaches, i.e., impact load, momentum, and energy between surfaces. These three elements can be outlined according to the following equations formulated by Zukas (1990).

$$dV = Const \tag{2.1}$$

$$F - m\frac{dv}{dt} \rightarrow \sum F_i + 1/2\rho v_i^2 = \sum E_f + 1/2\sum v_f^2 \tag{2.2}$$

Where:

ρ = Material Density

V = Volume

F = Force

m = Mass

v = Velocity

E = Stored internal energy

i = Initial condition

f = Final condition

(Faham, 2008) mentioned that one of these important factors may play a significant role in impact analysis nominated as elementary impulsive, and determined by:

$$\tau = \int_{t_0}^{t_1 \rightarrow} Fdt \tag{2.3}$$

Where;

τ = Impulsive load

F = Impact load

(Faham, 2008) considering the short duration of time ($t_0 - t_1$), and provided that the velocity of motion mass m which is changing from v_1 to v_0, without external force, then,

$$\tau = m\,(\vec{v_1} - \vec{v_2}) \qquad \textbf{(2.4)}$$

(Faham, 2008) has found at this stage Timoshenko and Goodier (1970) raised an important issue which they stated that as long as the impact zone is in the elastic region, a symmetrical load-time diagram can be obtained. Thus, at this stage, the maximum impact load (F_{max}) between the striker and the struck body can be calculated by:

$$F_{max} = \frac{(5m)^{3/5}\, k^{2/5}\, v^{6/5}}{4}$$

Where is k is a contact parameter which is dependent upon the geometrical and elastic properties of the bodies, and v is the impact velocity. They also mentioned that various types of stress wave develop that are dependent upon the energy imported into the target. There is no proper analytical equation to predict the behaviour of impact after the elastic region because this is a complex phenomenon requiring a separate investigation (Faham, 2008).

(Faham, 2008) also mentioned that the height of the impact hammer is below a certain level in the experiment, only elastic stress might be distributed but a higher velocity impact may result in in-elastic stress wave. Impact loading is classified as either hard or soft because it usually depends on the characteristics of the internal pre-requisite of the striker and the structures it strikes. If the impact hammer or missile is substantially deformed by collision with a hard structure, soft impact occurs but if the structures is deformed then hard impact has taken place.

The common problem of impact is extremely complex which involves large displacements, material non-linearity, elastic and plastic instability, post-buckling strength, coulomb friction and material behaviour under high strain rates (Kusano, T et al., 1992). Impact loading can be classified up to several specific factors such as velocity, impactor mass and angle of obliquity (V. Philippe et al., 2007), (J.P. Mougin et al., 2003), and (T.L. Teng et al., 2004). Hard impact of concrete is characterized by a sharply peaked force/time relationship (1 to 3x10-3 second), regardless of the approach velocity (S.H. Perry et al., 1989). This can be lead to spalling, concrete plug formation, back face scabbing and in the limit complete perforation of both reinforced concrete and prestressed concrete slabs. In contras, (C.S. Juan et al., 2006) recognized low velocity impact as impact velocities in range 2.5m/s to 4.0m/s with weight capacity around 2.0kg. Consequently, the impact create energy getting up 21.0 Joules which able to make the cracking followed by the localized crushing, shear failure and finally breakage. However, (B. Christian et al., 2006) categorized the impact into velocity and failure mode which abbreviated from Zukas's theory. At velocities below 228 m/s, the load-carrying behaviour of the entire structural part is activated. In the medium velocities, which ranged between 500 and 1200 m/s impact, principally leads to local effects and higher velocities of the projectile then cause explosive vaporization of the materials.

The understanding of concrete damages is important to avoid disorganize terminology. Therefore, a standardized description of the different modes of damage caused by impact loading is necessary to allow accurate comparison between various experiments. (S.H. Perry et al., 1989) define the following modes of concrete damages. Spalling is crater damage on the struck face while penetration of the missile into slab, scabbing, fracturing and expulsion of concrete are often at high velocities, form the face opposite 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 inclined cracking through the thickness of the slab and often in the form of a conical frustum. **Figure 2.4** shows the local and overall impact phenomena due to impact.

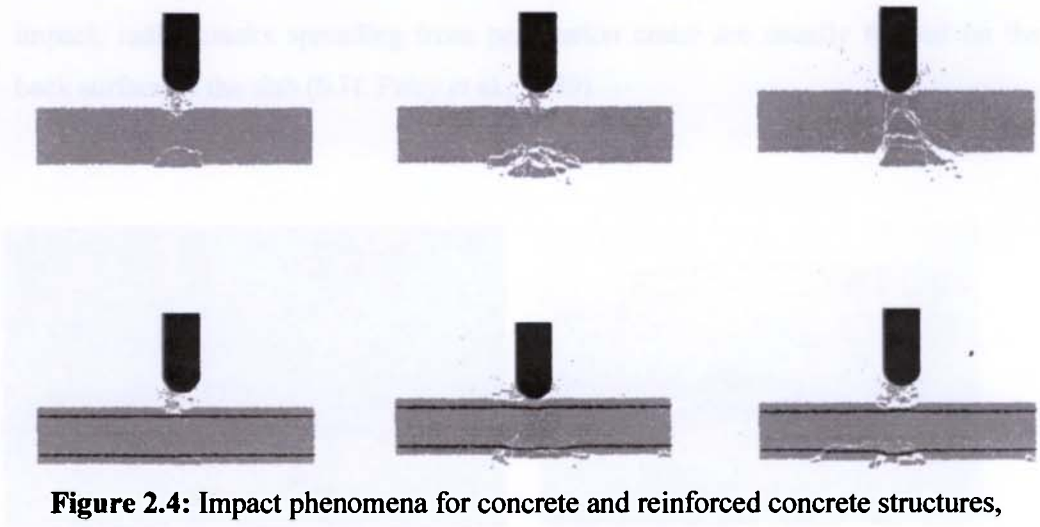

Figure 2.4: Impact phenomena for concrete and reinforced concrete structures, spallation on impact face, scabbing on back face and perforation.

In addition, (H. Wu et al., 2005) define spallation as the ejection of target material from the proximal face of the impacted structural target and it's controlled by the dynamic tensile behaviour of concrete and has been recognized as one of the main mechanisms of dynamic fracture of concrete. Meanwhile, (P.J. Thiele, 2005) define scabbing as the ejection of material from the back face of the impacted structural element opposite to 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 impact and runs through the material to a free edge. In that time, their contact is assumed to be no friction and impact in the central area of slab result no plastic strain appear in the support, therefore, the behaviour is consider being plastic (P.E Wright, 2008).

The wave is reflected there and transforms into a tensile wave that propagates in the opposite direction (S.H. Perry et al., 1989) and (C.S. Juan et al., 2006). **Figure 2.5** shows the real impact damage of scabbing and spallation. Generally, the area of scabbing will be much larger than the spall area, but not so deep. Once scabbing begins, the depth of penetration will increase rapidly, usually causing a concrete plug to be formed by inclined cracking through the remaining thickness of the slab. However, scabbing may occur either before, or as a result of, the concrete plug movement. Apart from the major damage caused at the point of contact during hard impact, radial cracks spreading from penetration crater are usually formed on the back surface of the slab (S.H. Perry et al., 1989).

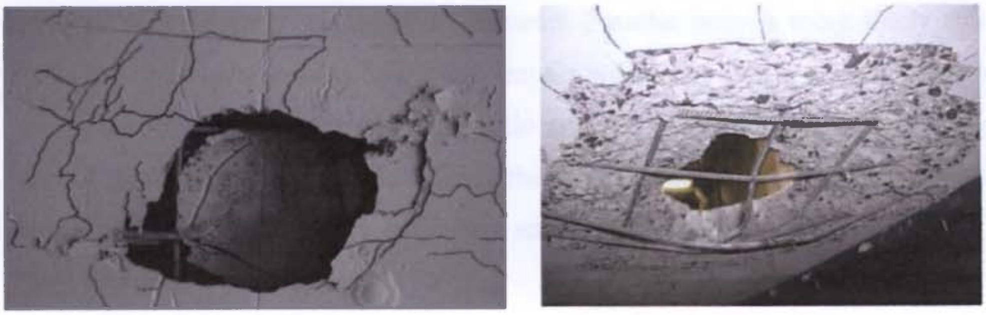

Figure 2.5: Experimental study of impact; a) top view of impact face, b) spalling on the bottom face

Bangash (1993) has classified the failure mode of reinforced concrete structures subjected to impact loading can be determined locally and globally. In addition, the phenomenon are classified as follows;

i. *Penetration*: The depth of the crater in the target at the impact zone.

ii. *Perforation*: Full penetration of the target by the hammer with and without exit velocity.

iii. *Scabbing*: Ejection of fragments from the opposite face of the target.

iv. *Spallation*: Ejection of the target material from the impact face.

v. *Global response*: It can be considered as global bending, shear and membrane action, as well as changing the mode of failure in concrete slab.

The interaction between impact body and reinforced concrete structure described by a number of factors that include relative masses, velocities, contact zone stiffness, frequency of loading, precision of impact, and the area of local energy absorbed (A.M. Remennokov et al., 2006). Similarly, (S.H. Perry et al., 1989) described that the form and degree of impact damage is heavily influenced by the ratio of slab thickness to impactor diameter. Smaller ratio is more likely to cause scabbing and concrete plug formation. Impact will occur over a relatively large area of the slab 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, also, can affect the type of failure and results for a pipe-shaped projectile have been discussed by (S.H. Perry, 1989).

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 (Q.M. Li et al., 2003). Relatively low contact velocities with small missile mass will lead to small contact forces and exercise the structure in the elastic. This type of impact will generally not cause any perceptible damage to the target. Besides that, time histories of impact loads and ratio of absorbed energy by reinforced concrete play the important role (Y. Sawamoto et al., 1998). On the other hand, (T.L. Teng et al., 2004) was discovered that oblique impact have influence to the failure pattern where at low impact velocity, the projectile is embedded but it can only penetrate one third then ricocheted from the slab. **Figure 2.6** shows how oblique impact has effect in concrete damage.

Figure 2.6: The effect of oblique impact on the concrete damage.

Reinforced concrete under impact loading shows different behaviour from that under static loading. The effect of impact velocity toward concrete damage can be understood following the impact damage chronological described by (S.H. Perry et al., 1989). As the impact velocity increases, spalling in the form of crater with an area larger than the cross-sectional area of the missile, may occur. Further increases of missile velocity will result in penetration with a depth greater than the depth of the spall crater and a cylindrical penetration hole only slightly larger than the diameter of missile. Some plastic deformation occurs within this increased velocity range, but the initial kinetic energy of the projectile is still to a large extent, expended in the rebound of the missile. Up to this stage, where target penetration occurs, the concrete slab as a whole can be treated as elastic for purpose of analysis. However, penetration of the target introduces predominantly inelastic behaviour. A further increase in missile velocity may produce cracking of 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.

2.1.3 Reinforced Concrete Slab

Reinforced concrete has become one of the most important building materials and is widely used in many types of engineering structures such as beam and slab. The economy, the efficiency, the strength and the stiffness of reinforced concrete make it an attractive material for a wide range of structural application. The application for reinforced concrete slab is used typically as floor, wall, deck and roof. Concrete is by nature a brittle material that performs well in compression but is considerably less effective when in tension. Thus, reinforcement in concrete is used 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 yielding of the steel and crushing of the concrete with the form of damage to be roughly the same under either static loading or impact. Based on this problem, (M. Zineddin et al., 2007), (H.

Abbas et al., 2004), (Q.M. Li et al., 2005) and (Q.M. Li et al., 2003) explained detail about the behaviours of concrete, reinforcing steel and the bond between reinforcing steel and concrete to make the behaviour of concrete subjected static or dynamic load become clear. Besides that, (Q.M. Li et al., 2003) explain that the behaviour of 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 impact and explosive loads. In addition to military application, the impact resistance of concrete structures is of particular concern to the nuclear industry (Q.M. Li et al., 2005). Concrete exhibits a large number of micro-cracks especially at the interface between coarser aggregate and mortar, even before subjected to any load. The presence of these micro-cracks has great effect on the mechanical behaviour of concrete, since their propagation during loading contributes to the nonlinear at low stress levels and cause volume expansion near failure. The response of a structure under load depends to 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 nearly linear elastic response up to about 28% of the compressive strength.

This followed by gradual softening up to the concrete compressive strength, when the material stiffness drops to zero. Beyond the compressive strength the concrete stress-strain relation softening until failure takes place by crushing. The relative weakness of concrete in tension and the resulting cracking is a fundamental factor affecting the non-linear behaviour of reinforced concrete structures. It is assumed that when concrete is subjected to a tensile stress it behaves like an elastic-brittle material (H.G. Kwak, 1990). If cracked concrete is supposed to remain a continuum and the material properties are then modified to account for the damage induced in the material. After the first crack has occurred, the concrete become orthotropic with the material axes oriented along the direction of cracking.

According to (H.G. Kwak, 1990) too, the response of concrete under tensile stresses is assumed to be linear elastic until the fracture surface is reached. **Figure 2.7** illustrates the condition of concrete, reinforcement and bond interaction between concrete and reinforcement which is compulsory to understand.

Figure 2.7: Concrete, reinforcement and 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. Reinforcing steel bars consider the elasto-plastic constitutive law and many investigations have already considered various constitutive laws concerning the strain rate's influence on material properties (Y.S. Tai et al., 2006) and (A.J.M. Ferreira et al., 2001). When the material is subjected to 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 used in concrete construction are obtained from 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, a range in which the stress drop off until fractures occurs. The extent of the yield plateau is a function of the tensile strength of steel. High strength, high-carbon steels, generally have a much shorter yield plateau than relatively low-strength, low carbon steels. Steel reinforcing bars used in reinforced concrete structures are usually round with protrusions (ribs or lugs). These protrusions are responsible for better bond characteristic between the reinforcing bars and the surrounding concrete. Steel bars have elasto-plastic behaviour, 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 (H.M. Gomes et al., 2001).

Bond is the interaction between reinforcing steel and surrounding concrete. The force transfer from steel to concrete can be attributed to three different phenomena, first, chemical adhesion between mortar paste and bar surface, second, friction and wedging action of small dislodged and particles between the bar and the surrounding concrete and third, mechanical interaction between concrete and steel. Bond of plain bars derives primarily from the first two mechanisms, even though there is some mechanical interlocking caused by the roughness of the bar surface. Deformed bars have better bond than plain bars because most of the steel force in transferred through the lugs to concrete. Friction and chemical adhesion forces are negligible but secondary and tend to decrease as the reinforcing bars start to slip. Since bond stresses in reinforced concrete are members arise from the change in the steel force along the length, the effect of bond becomes more pronounced at end anchorages of reinforcing bars and in the vicinity of cracks. In the simplified analysis of reinforced concrete, structures complete compatibility of strains between concrete and steel is usually assumed which implies perfect bond. This assumption is realistic only in region where negligible stress transfer between the two components takes place. In regions of high transfer along the interface between reinforcing steel and surrounding concrete such as near crack, the bond stress is related to the relative displacement between reinforcing steel and concrete.

CHAPTER HI

METHODOLOGY

3.1 Introduction

Basically, the study about finite element simulation of reinforced concrete structure slab under impact loading were carried out in several steps. Flow charts as show in Figure **3.1** describe the steps to be followed. The research was divided into three main categories, namely preliminary study of reinforced concrete under impact, modelling and simulation, and results analysis. The reinforced concrete slabs were modelled based on the experimental study conducted at Heriot Watt University in Edinburgh. All modelling and simulation were conducted using ABAQUS/CAE under explicit mode and the slabs were modelled with volumetric finite elements **(3-**dimensional). The reinforcement was represented by beam element whereby concrete slabs were modelled as solid element. For an accurate simulation of the structural response, it is necessary to use a realistic representation of the materials behavior under dynamic loads. For the concrete, the behavior properties were included some phenomena that are related to the damage under dynamic loads such as decrease in material stiffness due to cracking, stiffness recovery related to closure of cracks, and inelastic strains concomitant to damage. The results of simulation in term of damage wave propagation, the failure process of the steel reinforcement in concrete structures, the effectiveness of different mesh densities, the effect of the different projectile

725 mm in length and width, 76 mm in depth. The figure of the test set-up can be obtained in the next following chapter.

The experimental work has shown that the impact results in the slab realizing a peak loading followed by cracking of the concrete structure and load shedding. Although the impact causes failure, it is not sufficient to cause a catastrophic event such as perforation, penetration or major scabbing. The final crack pattern and the propagation of fracture are most important for further analysis and comparison to the results of the numerical simulation. Of particular interest is the region of the slab below the impact area. This is where the concrete fracture initially takes place and it is also the area where phenomena such as scabbing or spallation are generally witnessed.

3.3 Reinforced Concrete Slab Modelling

For the modelling part, the finite element software called ABAQUS software version 6.8-1 is used to simulate the low speed impact (impactor/projectile) on a simply supported reinforced concrete slab.

Before to start any modelling works, it is important to decide the system of units for the dimension, force, etc. **Table 3.1** shows the common system of units that will be used for ABAQUS's software users. For this study, SI unit (m) were applied.

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