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CRACK CRONOLOGY OF REINFORCED CONCRETE BEAM UNDER IMPACT LOADS

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Declaration

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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.

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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.

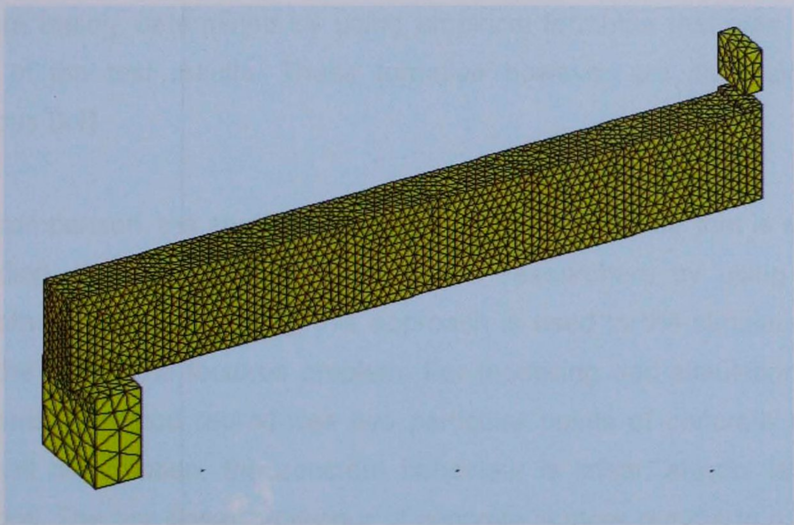

Figure 2.1: Example of three dimensional modelling of the beam and the impact block with different size mesh.

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.

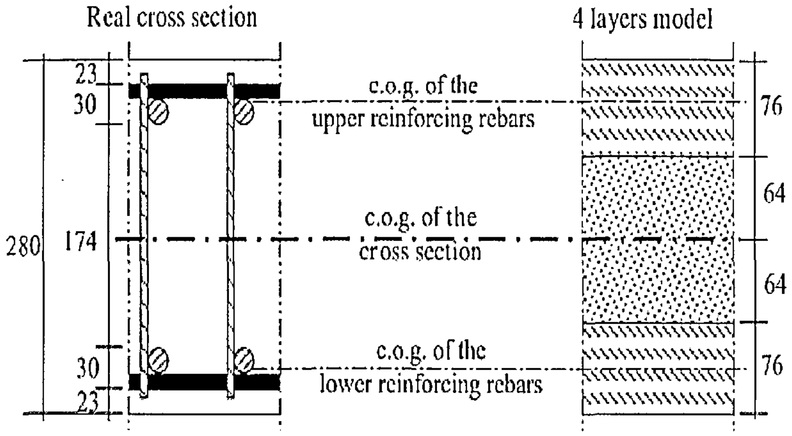

Figure 2.2: Cross section of the reinforced concrete structure with layers of the concrete.

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