Objective of the numerical simulation engineering essay

Engineering

INTRODUCTION

Background

Recent terrorist attacks on buildings around the world have prompted the need to study the behaviour of structures under blast loadings. Although explosions have occurred in the past mainly by accident, there has been an increase recently in planned explosions either for safe structural demolitions or as a form of attack on lives. Attacks of September 11 and the Oklahoma City bombing and accidental explosions in industries have increased the awareness of the vulnerability of structures to blast loadings. Concrete is widely used in the construction industry. Although concrete members are resistant to compressive stresses, the presence of reinforcements augments the durability and strength of the concrete members by increasing the resistance to tensile stresses under static loading. However explosions cause dynamic loadings on the concrete members, hence the need to investigate the effects of dynamic loading on the strength and durability of concrete members. Many research works have been published in the literature studying the effects of blast loading on reinforced concrete elements. Most of the research is aimed at response of elements such as columns to far-field loading. Few have investigated the response of reinforced concrete columns, in particular, to near-field explosions. It is widely known that the probability of terrorists’ attack increases with a decrease in amount of explosives. Thus, it is much more plausible for reinforced concrete columns to be attacked with small amounts of explosives at close-in distances than a larger amount of explosive at a larger standoff distance.

Objective of the Numerical Simulation

This thesis presents an investigation on the behaviour of reinforced concrete columns under near-field blast loading using AUTODYN software. The columns have a cross section 300×300 mm and height of 3 m; with the explosive charge mass of 100 kg at different standoff distances. The effects of reinforcement detailing on scabbing and spalling of concrete columns is investigated. Also, the effect of reinforcement detailing, scabbing and breaching on the residual capacity of the reinforced concrete columns is evaluated. The significance of this paper is establishment of critical standoff distance to prevent scabbing and cratering thus mitigating the effects of near-field blast on reinforced concrete columns.

Organization of Thesis

The thesis is organized into five chaptersChapter 1 presents an introduction to the project, explains the objectives of the study and outlines the scope of the study. Chapter 2 presents comprehensive literature review on the followingExplosions: causes and propagation of waves and effects on structural elementsThe AUTODYN software used for the numerical simulationConcrete Constitutive ModelsSteel Constitutive ModelsStress-Strain Behavior of Concrete and Steel under Dynamic LoadingScabbing and Spalling of Reinforced Concrete MembersChapter 3 describes the numerical simulation. This includes the followingThe setup of the modelThe material models usedValidation of the numerical modelChapter 4 of the thesis includes the results and the discussions of the results. This includesThe effects of blast on scabbing and spalling of Reinforced ConcreteThe strain development on the steel reinforcementsThe effects of the blast on the deflections of reinforced concreteChapter 5 outlines conclusions drawn from the discussions. This chapter also presents recommendations for future work.

Literature Review

Introduction

This chapter presents a literature review on the occurrence of explosions, the propagation of the blast waves and their interaction with structures. This chapter also includes literature on the AUTODYN software; the governing equations and usage. The materials models of concrete and steel are also reviewed in this chapter. Research on effects of blast loadings on concrete members is also reviewed.

Explosions

Explosions are the sudden release of energy and the rapid expansion of gases when an explosive detonates. Explosives are reactive substances in the solid, liquid and gaseous state, which contains high amount of potential energy. Explosions cause the expansion of hot gases which forces out of any confined volume or space. Most of the energy released by the explosion is contained in a layer of compressed air, which forms at the front of the expanded gas volume. The released potential energy is accompanied by heat, light, sound and high pressures. Explosions cause the expansion of hot gases which forces out of any confined volume or space. Most of the energy released by the explosion is contained in a layer of compressed air, which forms at the front of the expanded gas volume. Pressure of the blast wave instantaneously increases above ambient atmospheric pressure. The high pressure is known as the incident overpressure and decays as the wave propagates.. Explosives are reactive substances, which contains high amount of potential energy. Explosives can be in the solid, liquid or gaseous state. Pressures generated can be as high as 300 kilobars with temperatures ranging between 3000 to 4000 degrees Celsius [8] . Explosives weighing up to 5 kg of TNT are termed as small explosives. Medium sized explosive devices weigh between 5 kg and 20 kg of TNT. Large explosive devices weigh up to 100 kg TNT and very large explosive devices weigh up to 2500 kg of TNT [7] .

Classification of explosions

Nature of the explosions

Explosions are classified based on the nature of the explosions: physical, nuclear and chemical explosions. Physical explosions: Physical explosions include the explosion of compressed gases in containers. Also, volcanic eruptions and violent mixing of liquids at different temperatures are other examples of physical explosions. Nuclear explosions: Nuclear explosions are caused by the sudden release of energy through the fusion or the fission of atomic nuclei. This is due to the redistribution of neutrons and protons. An example of atomic nuclei fusion is the joining of hydrogen isotopes, Deuterium and Tritium while splitting of isotopes of Uranium is an example of nuclear fission. Chemical explosions: Chemical explosions are caused by the rapid oxidation of fuel elements such as carbon and hydrogen atoms. The oxidation leads to the production of enormous energy compared to physical explosions. Chemical explosives contain high amount of oxygen which aids the oxidation process.

Planned and accidental explosions

The classification of explosions is also based on the manner of occurrence of the explosions. Controlled explosions are used safely to enhance life in mining, engine combustion and controlled explosive demolition of structures. However, some planned explosions such as terrorist attacks leads to loss of lives and the destruction of properties.. Examples of terrorist attacks on structures include the Oklahoma City Bombing in 1995, The World Trade Center Building New York in 1992, Ben Weider Community Centre Bombing Canada in 2007 and the bomb explosion at the Cuban Consulate in Montreal in 1980. The Oklahoma City Bombing in 1995 was caused by fertilizer-based high explosives of mass 1800 kg while 900 kg of explosives was used in the attack on the World Trade Center Building. [7] . Accidental explosions occur at locations that manufacture, store and transport explosives.. The Texas City explosion in April 16, 1947 an example of accidental explosions remains the worst industrial accident in the history of the US. The disaster was due to the explosions of ammonium nitrate fertilizer on two ships: the Grandcamp and the high flyer. The explosions of the two ships at intervals of 16 hours triggered explosions of oil tanks and burning of structures. This resulted in severe damage to property and loss of lives Error: Reference source not foundError: Reference source not found.

Activation mechanism

Explosives are also classified based on the activation mechanism. There are two types of activation mechanism: high explosives and low explosives. High explosives detonate while low explosives deflagrate. Deflagration occurs when explosive material decomposes at speed lower than the speed of sound whiledetonation produces high intensity shockwave above the speed of sound. The detonation velocity lies between 1500 and 9000 m/s. Low explosives produce smaller amplitudes of pressures with longer durations while high explosives produce high pressures with short durations. Explosive that easily detonates by simple ignition from a flame spark or impact is known as a primary explosive. Examples of materials that constitute primary explosives are mercury fulminate and lead azide. Secondary explosives detonate less easily in comparison to primary explosives. Examples include TNT and RDX (cyclonite, hexogen). Secondary explosives are used as main explosive charges in shells and cartridges [8] .

TNT- Equivalence

The amount of energy released during an explosion determines the magnitude of the explosion. The magnitudes of explosions for different explosives are calculated based on TNT equivalence. This is because there are a large number of explosives and it is difficult for engineers to determine the magnitude of every explosive without the use of an equivalence. The TNT equivalence relates the magnitude of any explosive to the magnitude of TNT. TNT is commonly used because, it is pure, readily available, easy to handle and lots of research have been conducted using TNT. TNT detonation generates blast energy of 4610 joules per gram. The comparison for the TNT-equivalence is based on the heat of combustion, heat of detonation and the detonation energy as stated by Maienschein [9] . Other factors such as the shape and number of explosive items also affect the TNT-equivalence. Wharton et al. [10] stated that the TNT equivalence values are dependent on the scaled standoff distance and on data the equivalence was derived from, that is the overpressure data or the impulse data. Most explosives studied showed that TNT equivalence calculated from impulse data has a greater dependence on distance than TNT equivalence calculated from overpressure data as shown in Error: Reference source not found and Figure 2Figure 2- The dependence of TNT equivalence by overpressure on scaled distance [10]Figure 2- The dependence of TNT equivalence by impulse on scaled distance [10]

Blast waves from high explosives

Introduction

An explosion reaction generates hot gases at high pressures ranging from 100 to 300 kilobar and temperatures ranging from 3000 - 4000 degrees Celsius. These high temperatures and pressures lead to violent expansion of the hot gases. This violent expansion pushes out the surrounding air. As a result, a layer of compressed air is formed in front of the hot gas, which contains most of the energy released during the explosion. This layer of compressed air is termed as the blast wave. Over time, the pressure decays to atmospheric pressure as the blast wave propagates through the air. As the distance away from the source of the explosion increases, the overpressure drops. The gas cools and the pressure falls below the atmospheric pressure creating a region of underpressure known as negative phase of the blast wave. After this stage, equilibrium occurs and the blast pressure returns to the atmospheric pressure [8] .

Scaling laws of blast waves

The most common blast waves scaling is known as the cube root scaling. This scaling law was formulated by Hopkinson and Cranz [7[8]]. This is commonly called the Hopkinson-Cranz scaling law. The cube-root scaling law compares two charge masses of the same material and and the respective diameters and. According to the cube- root scaling law, is directly proportional to and is directly proportional to leading to the equation below

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In developing the same overpressure for the two charge masses, the ranges of the charge mass would vary. Charge mass with a rangewould produce the same overpressure for a charge mass with range . This results in the formulation of the scaled distance equations

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where Z is the scaled distance. The scaled distance relationship presents an efficient way in blast data analysis [7] .

Blast wave pressure profiles

Exponential functions are used in describing the pressure- time history of blast waves. The Friedlander equation is the most commonly used exponential function as shown below in the relation

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where P(t) is the pressure at time t is, ρso is the peak overpressure and is the waveform parameter. The pressure time history can also be idealised into a linear function. This conservative approach gives satisfactory values in design. The pressure time history is also idealised by maintaining the same impulse as the exponential function. The area under the actual decay curve and the idealised linear curve are equal if the impulse is maintained in the idealisation [8] . Figure 2- Blast Pressure Profile

Blast wave reflections

Explosions occurring close to surfaces reflect off the surfaces increasing the overpressure of the blast wave. The surfaces are usually the ground and the face of structures. Figure 2- Normal reflection of planar shock front off the ground

The AUTODYN software used for the numerical simulation

Introduction

The AUTODYN software initially designed by Century dynamics is now part of the ANSYS workbench. AUTODYN is an explicit analysis tool for modelling nonlinear dynamics of solids, fluids gases and the interactions between these bodies. AUTODYN is used especially to analyse the stress, strains and deformations of these bodies. Codes designed for nonlinear dynamic problems are known as hydrocodes. AUTODYN is equipped with a user-friendly interface for modelling, processing and post-processing of problems. . Error: Reference source not found. AUTODYN has also been incorporated with material constitutive models and material equations of state. The equations of state employed in AUTODYN include linear, polynomial, shock, ideal gas, JWL, orthographic Tillotson and the PUFF models while examples of constitutive models used in AUTODYN include hydrodynamic, elastic, brittle, Von Misses, Johnson Cook, piecewise hardening models. The major role played by the material constitutive models is linking the stresses developed to deformation and internal energy. The equations of states express the relationships between the pressure, specific volume and specific energy. The equations of mass, momentum and energy are coupled with material descriptions to solve problems, with the software adapted for accurate analysis of penetration, impacts, and blast explosion events events Error: Reference source not foundConservation of mass:

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Conservation of momentum:

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Conservation of energy:

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Decomposition of stresses:

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Equation of state:

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AUTODYN uses the finite difference, finite volume and finite element methods to analyse problems. The finite element solvers are used in modelling computational structural dynamics and the finite volume solvers for modelling fast transient Computational Fluid Dynamics problems. AUTODYN also uses a mesh-free particle solver in solving problems with large deformations. The governing equations under the finite methods are discretized into the second order central difference schemes. The second order central difference scheme is based on an explicit time integration method, which is conditionally stable. The stability condition is met by using the Courant-Friedrich-Levy criterion to control the time step. The Courant-Friedrich-Levy criterion states that the time step �" t is defined as:

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Where c is the velocity of the sound signal and �" x is the grid spacing [16] . Shock waves produced in solving problems are mathematically discontinuous. This problem is overcome by the introduction of an artificial viscosity. The artificial viscosity smooth out any discontinuities, this allows the hydrocode to continue. The artificial viscosity is formulated as:

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Where ρ is the current local density, CQ and CL are constants, d is a typical c is the local sound speed and is the volume change [16] .

Examples

Examples of real projects employed in the use of AUTODYN include:

Designing mine protection schemes for personnel carriersAircraft impact risk assessment for power stationsBuilding protection measures and insurance risk assessment for blast effects in city centresDesigning the shielding system on the international space stationOptimisation and design of armour and anti-armour systems

Lagrange solvers

Lagrange solvers use a mesh based method with the grids used placed inside the materials. The grids, which are structured IJK mesh, move with the material, hence no transport of material from element to element. The Lagrange solvers are used for modelling solid materials and structures. The Lagrange solvers are appropriate for following the material motion and determining deformations in regions of large displacements and low distortions. The merit of the Lagrange solvers lies in the computational efficiency and ease with which complex constitutive models can be incorporated into the solver. In extremely deformed regions, the numerical grid of a Lagrange solver can be severely distorted. This usually leads to inaccuracy and has adverse effects on the integration time step. These issues are overcome by using erosion techniques [21] . In a Lagrange solver, the velocity (u), coordinate (x), force (F) and mass (m) are defined at corner nodes while stress (σ), strain (ε), pressure (p), density (ρ) and energy (e) are defined in the centres as shown in the figure below: [29]Figure 2- An Example of a Lagrange Grid [29]

Euler solvers

The Euler solvers use also a mesh-based method to analyse problems. The grids are placed in space while the material moves through the Euler grid. The Euler solvers are used for modelling gases and fluids and large distortions of solids. Examples of such modelling include the detonation of gas explosives. For solid structures with large distortions, additional computations are required to transport the solid stress tensor and the material history through the grid. Large deformations do not result in grid distortions. This is due to the fixed grid. There are three types of the Euler solvers: conventional and Godunov-type and Flux corrected transport (FCT) [4] . The Godunov type Euler solver solves the local Riemann problems at cell interfaces while the FCT type Euler solver uses a two-step method, the convective step and anti-diffusive step. The anti-diffusive step corrects the numerical diffusion error made by the convective step [23] . Figure 2- An Example of an Euler Grid [29]

Arbitrary Lagrange Solvers (ALE)

This is a hybrid of the Lagrange and Euler Solvers, which is used for solid, fluid and gas problems. The ALE is also a mesh-based solver, which facilitates the automatic rezoning and used for specialized problems. The main advantage of the ALE is that, it can reduce the problems caused by the severe mesh distortions, which is encountered by the Lagrange solver. However, an additional computational step is required by the ALE to move the grid and remap the solution unto the new grid [4] . Figure 2- An Example of an ALE Grid [29]

Mesh free solver

This type of solver uses a particle based smooth particle Hydrodynamics (SPH) method. The SPH is a relatively new method in comparison with the Lagrange and Euler methods. This solver is used for problems with high velocities, fragmentations and large deformations. The SPH was implemented in the AUTODYN software in 1995 [15] . The SPH method discards the need for numerical grid in solving spatial derivatives. The SPH method requires relatively higher number of particles to locate current particles. This makes the computational time relatively expensive [20].

Coupled multi solver approach

AUTODYN uses a coupled multi solver approach to arrive at solutions. These solutions are obtained through the interactions of the solvers. There are two main interactions, namely the Lagrange-to-Lagrange interaction and the Euler to Lagrange interaction [15] .

Lagrange to Lagrange interactions

This is the interaction between two Lagrangian grids. Two main interactions zones are used to detect when a node enters a grid. The Gap size acceptance and the trajectory are used. The gap size acceptance is more suited for structured grids while the trajectory method is used for unstructured grids [15] .

Euler to Lagrange interaction

The Euler/Lagrange interaction is best suited for fluid/structure interaction. The Euler region acts as pressure boundary on the Lagrange at the Euler-Lagrange interface while the Lagrange body provides a geometric constraint to the Euler Region [15] .

Concrete Constitutive Models

Introduction

Numerical computations require constitutive models to describe the behaviour of structural members. Interest in this subject led to formulation of different models as attempts were made to understand the behaviour of the structural members. This chapter reviews different types of concrete models and the associated limitations. This section details some concrete models that are used under dynamic loading. Commercial numerical hydrocodes require sound constitutive models to accurately predict results. The constitutive models should be able to represent the mechanical process of the material under different loading rates. Although concrete is a heterogeneous material, it is impractical to formulate the constitutive models based on the heterogeneity. This is because; it requires the concrete to be modelled on a meso-scale. Due to this limitation, concrete is treated as a homogeneous material leading to, constitutive models for concrete being modelled on a macro scale. Various studies have been conducted over the years to improve the macro-scale models. The complexities of the models have varied over the years. The model parameters play important roles in determining the accuracy of the models. Most concrete models developed in AUTODYN have similar features of brittle materials. These features are the pressure hardening, strain hardening and the strain rate dependency. Stress and strains are treated separately by hydrocodes in volumetric (ρ, μ) and deviatoric portions (Sij, Ɛij) [33] .

The equation of state of concrete

The concrete equation of state initially proposed was denoted as in equation (. This did not account for the porosity of concrete. Due to concrete having 10% porosity, Herman et al. [36] proposed the inclusion of the porosity in the EOS of concrete as shown below:

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The porosity,

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Where Plock is the pressure at total compaction and Pcrush is the initial pore core pressureThe introduction of the effects of porosity on compaction of concrete during dynamic loading combines the thermal expansion due to both the shock heating and porous compaction [33] [36] .

Johnson and Holmquist concrete model

This model was developed to give a comprehensive description of the concrete material under general loading conditions. This model was developed in 1993 by Johnson and Holmquist. This model is also known as the JH model. The concrete material is considered as linear elastic until failure is reached. Damage of the concrete accumulates with increase in loading. This occurs until total failure is achieved. The material maintains a residual state beyond total failure. The initial failure surface is calculated using the relation below:

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Where * denotes a normalized quantity, P* indicates the normalized pressure with respect to fc, Ɛ* denotes the equivalent plastic strain rate. This is normalized with respect to a unit strain rate. A, B, N and C are constants. SMAX is the maximum strength. Where J2 is the second deviatoric stress invariant and fc is the uniaxial compressive strength of concrete. The post-failure surface is calculated as:

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D accumulated by inelastic deformations describes the material damage, ranging from 0 - 1

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Where is the equivalent plastic increment and is the plastic volumetric strain increment. This is done by reducing the cohesion strength value of the initial failure surface. The JH model does not consider the third invariant J3. During the volumetric compaction process, the plastic volumetric strain allows for the reflection of the concrete material when the material loses its cohesion strength. This contributes to the damage of the material. The pressure-dependent fracture strain is defined below as:

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Where T* is the normalized concrete uniaxial tensile strength. FSMIN was introduced in the formula to prevent the fracturing of concrete by low magnitude tensile waves, although it was difficult to determine the value for FSMIN especially for the behaviour of concrete under pressure values below fc/3. This limitation is overcome by differentiating between the compressive and tensile fracture strains. Based on equation (), the JH model expends the strength surface by a factor of (1 + C In Ɛ*). This is done when modelling the strain rate effect. This enhancing approach makes determining C difficult. The strain rate for compression and tension are different. In addition, data obtained from experiments correspond to radial strength enhancement paths and not to strain rate enhancement path. The yield surface is not smooth over the pressure range for the JH model; rather the yield surface has a sharp cut-off plane, this cause a non-differentiality at the intersection location. The normalised parameters and stress variables make it easier to implement the JH model in other strength models. However, the JH model is incapable of solving every static and dynamic event. Although experiments show inelastic deformations with hardening before peak load and reduced failure strength on meridians off triaxial compressions, these are not exhibited by the JH model [33] [34] .

Gebbeken and Ruppert concrete model

The GR model was developed from the JH model. This model included some modifications and enhancements. The GR model added a third stress invariant in defining the strength surfaces and a different expression of the yield surfaces.

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Where τ0 is the normalized octahedral shear stress with respect to fc, σ0 is the normalized octahedral normal stress with respect to fc, b is the normalized hydrostatic tensile limit, a also denotes the upper limit for τ0 as σ0 approaches positive infinity. The power d is a parameter that controls the shape of the yield surface. The variable c reflecting the third stress invariant influence is defined below as:

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Where the parameters ct and cc are associated with the tensile and compressive meridians.???? is the Lode angle as shown belowFigure 2-Deviatoric cross section of strength surfacesEquation () Error: Reference source not found facilitates a clear physical interpretation of the free parameters, making the determination of these parameters easier. The yield surface as defined by equation () Error: Reference source not found is smooth over the pressure range. The material damage is taken into account during the strain rate enhancement. A hyperbolic function is used to cap the magnitude of the enhancement factor for very high strain rates as shown below:

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Fm is the limit value of the rate enhancement factor when the strain rate approaches infinity. Fm and Wy are both functions of the damage index D. D2 as defined below is the concrete damage due to the volumetric compaction

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WhereBoth D1 and D2 are combined to determine the overall damage as shown below

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The RHT model

The RHT model, an enhanced form of the JH model was developed by Riedel et al [33] . This model took into account the third invariant and the strain hardening. The RHT model also included an independent fracture surface and incorporated a rate dependent hydrostatic tensile strength for concrete. The fracture surface facilitated an easy modelling of the softening process of the material. The failure surface is defined as:

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Where fc and ft are the uniaxial compressive and tensile strength of the material respectively, the constants A and N are the model parameters. The rate factor denotes the dynamic increase factor of the tensile strength as a function of the strain rate [37] .

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Both are the material constants

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The lode angle is a function of the second and the third deviatoric stress invariantThe deviatoric section has a triangular shape at low pressures and circular shape at high pressures. The concrete material exhibits a brittle behaviour under low pressures and ductile behaviour under high pressures [33] [34] [35] . The rate dependence of the hydrostatic tensile strength of the material adopted for the RHT model is described using the following relation:

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A factor equal to the DIF is used to enhance the material hydrostatic tensile strengthThe material strain hardening is accounted for in the RHT model with the introduction of an elastic strength surface as shown below:

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Where is the upper cap pressure, at this pressure the yield surface intercepts with the hydrostatic axis. is the lower cap pressure, pressure where the uniaxial compression path intercepts with the elastic surface [35] . The model also introduced an independently defined residual strength to describe the strength of the crushed material

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Where the sign function is defined as:

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The loading and post loading surfaces are defined as

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The definition of the damage D is shown below

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�" Ɛp is the accumulated plastic strain

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D1 and D2 are input parametersThe parameters Ɛpl and Ɛpl-presoftening are shown in the figure belowFigure 2 - Illustrations of strain hardening, RHT model [34]Figure 2- Failure Surface, RHT model [37]

Steel Constitutive Models

Johnson and Cook (JC) developed an AUTODYN constitutive model for steel [41] . This was specifically designed for 4340 steel, an alloy of Nickel, Chromium and Molybdenum. JC used a torsion test data to determine the parameters needed to formulate the constitutive model. In formulating the model, JC assumed that an average shear strain occurs using the torsion test data. The strength model is formulated using the Von Misses tensile stresses [41] .

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Where Ɛ is the equivalent plastic strain, Ɛ* is the dimensionless plastic strain, T* is the Homologous temperature. C1, C2, C3, n, m are the steel material constants. The expression [C1+C2 Ɛn] represents the stress function when Ɛ* = 1 and T* = 0. The second and third expressions of equation () represent the effects of strain rates and temperature on the material. The fracture model developed by JC is also dependent on the strain rate, temperature and pressure [41] . The fracture is represented in equation [number] and occurs at D = 1.

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Where σ* is the dimensionless pressure-stress ratio, σm average three normal stress, σ_ Von Misses equivalent stress. D1, D2, D3, D4, D5 are material constants. Also the strain to fracture decreases as the hydrostatic stress σm increases [41] . The JC model however is not able to accurately predict the strength of the material with strains exceeding 103 per sec. this is because at large strain rates, the yield stress increased enormously. This resulted in a revised form of the JC model in 1997 [42] . This revised form included an upper bound for the yield strength. The yield strength varied with the logarithm of the dimensionless strain. The strength model of the revised form is formulated as

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where C4 and C5 are additional constants. Strain rate sensitivity of the material is enhanced by the introduction of the expression 1/ (C3 - In Ɛ*). C5 is the natural logarithm of the critical strain rate level. The contribution of the strain rate sensitivity enhancement term becomes zero at low strain rates. Hence the revised JC model tends towards the JC model. The deviation of the revised model from the original JC model is controlled by C4. Also a peak strain rate sensitivity factor is introduced to prevent unrealistic occurrence of an infinite yield strength as InƐ* approaches C5. This factor is defined as

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The revised JC model assumes that the peak value constant (C6) [42]

Explosive properties

Pressures generated in explosions are described using the Jones-Wilkins-Lee equation:

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where is the hydrostatic pressure, is the specific volume is the specific internal energy, are the material parameters [17] .

Stress-Strain Behavior of Concrete and Steel under Dynamic Loading

Structural materials used in construction are sensitive to loading rates. Hence, properties of materials used in reinforced concrete structural members are all dependent on the strain rate [12] [13] , [14] . Structural member behaviour under blast load differs with straining rate during the duration of the loading. The loading rate affects the strength, ductility, stiffness and this is most significant under very high loading rates. Both concrete and steel exhibit increase in strength under higher loading rates Error: Reference source not foundError: Reference source not found. Formulating models to account for every change in the strain rate of a structural member is very complex and hence an average of the strain rate is used for constitutive models. The complexity also increases for nonlinear materials. The use of an average strain rate has produced accurate results Error: Reference source not foundError: Reference source not foundError: Reference source not foundBlast loading increase the static strain and hence enhancement factors are used to increase the material properties of structural members. Watstein et al. [11] used enhancement factors of 1. 4 and 1. 2 for the strength and young's modulus of a grade 30 concrete. Figure 2- Magnitude of strain rates expected for different loading cases. [13]The stress strain behaviour of concrete under dynamic loadings varies with increase in strain rate and knowledge of the behaviour of concrete under such high rate dynamic loading would better predict the response of concrete. Several experiments have been conducted in the past to study the behaviour of concrete and this includes the Split Hopkinson Pressure Bar experiment. The Split Hopkinson Pressure Bar was originally used in determining the dynamic properties of Aluminum alloy with strain rate per second. The Split Hopkinson Pressure Bar is made up of three parts; the incident bar, the transmitted bar and the specimen. The specimen is sandwiched between the incident bar and the transmitted bar. A striker at the end of the incident bar generates stress pulse on impact through the incident bar. The pulse propagates through the incident bar and are partly reflected and transmitted at the interface of the incident bar and the specimen. The percentage of reflected pulse and transmitted pulse largely depend on the impedance between the two materials. Zielinksi et al. [38] noted that about 95% of the stress pulse is transmitted at the interface between aluminum bar and concrete specimen. Strain gauges in the bars measure the strain rate in the bars. The measurement of the transmitted pulse occurs in the transmitted bar. Both compressive and tensile test can be carried on the specimen as indicated by Lee et al. [39] The measurement of the tensile pulse occurs after the wave has reflected off the end of the transmitted bar [[1] , [39] , [38] , [18] . Figure 2- The Split Hopkinson Pressure Bar

Scabbing and Spalling of Reinforced Concrete Members

Scabbing is the removal of concrete material from the back surface of a concrete structure subjected to blast loads. Compressive waves propagate through the concrete material and are reflected off any free surface. Such compressive waves are developed under high impact or blast loading [1] . Scabbing and spallation are used interchangeably in the review to denote de same meaning. Many researchers have researched into the behaviour of concrete materials and concrete structural elements. Both numerical models and experiments have been conducted over the years to determine concrete response to dynamic loadings. The numerical models started with one-dimensional models and later three-dimensional models were introduced as computer power increased. The one dimensional numerical model was constructed by Nash et al. [1] reviewed the Hopkinson bar experiment in which explosives denoted in contact with steel plates caused scabbing of the back surface of the plates. Scabbing varies for both brittle and more ductile metals. Nash et al. [1] developed a numerical model to determine the behaviour of concrete walls under dynamic loading. The paper investigated the propagation of stress waves though concrete walls and the initiation of scabbing of the concrete walls. Previous literature reviewed by Nash et al. [1] highlighted that two numerical codes were developed to determine the propagation of stress wave along a prismatic bar. The first code was written for a one-dimensional bar and the second code was written for a two dimensional bar. The codes were written to study the occurrence of spall on the prismatic bar. Nash et al. [1] modified the codes reviewed, to describe the concrete spallation. This was because spallation of concrete occurs at lower stresses than that of prismatic bars. Nash et al. [1] made no provisions to determine the effects of reinforcing steel on the wave propagation. A minimum spall velocity was needed to dislodge the spall fragments from the concrete wall and the minimum velocity has a relation to the energy losses during fracture. Two spall velocities were chosen based on comparison between experimental and analytical results. These Spall velocities that were 600 in per sec and 1200 in per sec were chosen because most recorded spall velocities ranged from 400 to 600 in per sec and also there were no records of spall velocities exceeding 1200 in per sec [1]. Xu and Lu [2] and Zhou et al. [3] numerically investigated the spallation of concrete plates under blast loading using a three dimensional model. Xu and Lu [2] stated that stress waves propagation through concrete could be altered from planar to non-planar due to divergence and spatial distribution of the waves through the concrete, which was not considered by Nash et al. [1] Xu and Lu [2] employed the use of the erosion algorithm. The erosion algorithm offers a view into the physical fracture of the concrete material. The element of the concrete material is deleted under the erosion algorithm when it reaches a critical value. The numerical model by Zhou et al. [3] constituted a quarter of the concrete slab due to symmetry. The detonation was modelled as 2D and mapped to the 3D concrete slab model just before the blast wave reached the concrete model. The two failure modes in the numerical simulation were caused by high-speed stress wave propagation and by the deformation due to free vibration. Concrete fragments are usually ejected due to high-speed stress wave propagation as this occurs at high strain rate. Hence, concrete fragmentation and spalling are rare under low strain rate. A low critical damage value of 0. 22 was chosen to predict the spalling at the bottom surface of the concrete slab. The spalling at the bottom surface of the slab was caused by tensile failure. The value of 0. 22 for the critical damage was chosen because, this agreed with experimental results [3] . Nash et al. [1] and Xu and Lu [2] categorised the behaviour of concrete under three main categories: no damage, threshold for spall and medium spall categories. The no damage category is the category that starts from the initial state to when barely visible cracks appear while the threshold for spall category is the category which shows some visible cracks on the surface of the concrete, a large bulge and some concrete fragments and the medium spall category shows shallow spalls and spall penetration to about a third of the concrete plate thickness.

Equations to predict the threshold of spall

Nash et al. [1] developed an equation that could predict the threshold of spall of the concrete after comparing results with obtained in the numerical model with experiments conducted.

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Where R = the standoff distance in inches. W = the charge mass in Ibs. A and B are constants derived from regression analysis. The equation was developed using curves plotted for the one-dimensional model. The threshold spall damage curves formed straight lines using a log - log plot leading to the above equation. Xu and Lu [2] developed an expressions based on the numerical results to determine the threshold of spall using a three dimensional model

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Where is the charge mass and is the standoff distance

Thesis Justification

Numerical Simulation

Introduction

A three dimensional model was built in AUTODYN to investigate the behaviour of the RC columns subjected to blast loads. The sub sections in this chapter outline the dimensions of the numerical model, constitutive models used and the interactions between the RC columns and the blast loads.

Geometry of model

The numerical model was created for a column of 300 by 300 mm cross section with vertical height of 3 m. The column was reinforced with a 25 mm diameter steel rebar. The bar had the same height as the column. Four of the longitudinal rebars were used in reinforcing the column. Reinforcing ties of diameter 10 mm were placed around the main bars. The tie spacing varied for different configurations. Three different tie spacing of 75 mm, 150 mm and 300 mm were used in modelling the concrete column. Figure 3 shows the dimensions of the column including the clear cover of 40 mm. [Why did you choose those dimensions, this dimensions were chosen in relation to experimental work]. Figure 3 - Dimensions of RC column

Material Models used in Simulations

The concrete material model

The RHT concrete material model was used in modelling the concrete. The RHT model reviewed from literature was able to accurately predict the behaviour of the concrete under blast loadings. However, modifications were made to the General RHT model found in AUTODYN to suit the concrete parameters used for the simulations. The parameters of the concrete were chosen in accordance with results from tests carried on concrete cylinders. The parameters shown in table () were used in the material model.

The steel material model

The steel material model used for simulating the behaviour of the steel reinforcement for both the main bars and the links was the 4340 Steel model developed by Johnson Cook. Unlike the other steel material models, the 4340 Steel model accurately interacts with the concrete and the blast load. Table () shows the parameters of the reinforcement used for the simulation.

The explosive material model

An inbuilt explosive model for ANFO was used for the numerical simulation. This was compared with results from CONWEP for different charge masses and ranges. This was to determine the accuracy of the explosive model. Figure 3 shows the comparison of 100 kg ANFO charge mass at 4 m from the target. The maximum incident pressure AUTODYN is 895 KPa while 1013 KPa was noted for CONWEP. The maximum pressure values occurred at time 2. 06 sec and 2. 23 sec for CONWEP and AUTODYN respectively. Although AUTODYN predicted the negative phase of the blast, CONWEP could not because CONWEP does not have that ability. Figure 3- Pressure-time history plots for AUTODYN and CONWEP

The air model

The air was modelled using ideal gas equation. The internal energy entered into the model was…… this was to achieve ambient air pressure

Blast load modelling

The explosives were initially modelled as 2D and remapped unto the 3D numerical model just before the blast waves reached the concrete. The 2D model was remapped into the 3D numerical space as initial conditions. This saved time and also allowed for a very fine mesh for the 2D model. Figure 3 shows the 2D model for the explosion. C: UsersAbladeyDropboxair_0003. gifFigure 3- A 2D model showing the ANFO and Air

Elements of the model

The concrete part of the column was modelled as Lagrange elements. This was because; Lagrange elements are used for modelling solid elements where the element is fixed within the grid. The reinforcement bars were also modelled using Lagrange elements. The air and explosives however were modelled as Euler elements. The Euler grid allows the elements to move through while the grid remained fixed, hence best suited for the air and explosives. The use of Godunov-type Euler solver is appropriate for this simulation, because, the strength of the blast wave from the 2D model is transferred when remapped into the 3D numerical space. Figure and figure show the numerical model for both the Lagrange and Euler Elements.

Joins

Boundary conditions

Gauges

Interactions of Elements

Controls

Output

Validation of Numerical Model

Results and Discussions

Conclusions and Recommendations