THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Concrete Structures Subjected to Blast Loading

Fracture due to dynamic response

JONAS EKSTRÖM

Department of Civil and Environmental Engineering
Division of Structural Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY

Göteborg, Sweden 2015

Concrete Structures Subjected to Blast Loading
Fracture due to dynamic response
JONAS EKSTRÖM

Thesis for the degree of Licentiate of Engineering 2015:04
ISSN 1652-9146
Department of Civil and Environmental Engineering
Division of Structural Engineering
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: +46 (0)31-772 1000

Chalmers Reproservice
Göteborg, Sweden 2015

Concrete Structures Subjected to Blast Loading
Fracture due to dynamic response
Thesis for the degree of Licentiate of Engineering
JONAS EKSTRÖM
Department of Civil and Environmental Engineering
Division of Structural Engineering
Chalmers University of Technology

Abstract

The interest for building safety with regards to highly dynamic events such as close by explosion has accelerated after the recent decades of terrorist attacks. The interest has expanded from civil defence shelters and pure military targets to also include civil buildings used for different civil functions. Due to the rather rapid shift of area of interest, the general engineering community lack much of the knowledge and tools with which to design and evaluate structures with respect to dynamic events with very fast transient and high magnitude of peak loads. In this thesis, two studies of concrete structures are presented. Both studies focused on describing concrete with a combined damage and plasticity model. The aim was to study how different numerical models perform during highly dynamic events. Two main studies are presented.

In the first study the response in a concrete wall subjected to shock wave blast, leading to spalling failure was investigated. This situation is important since spalled-off fragments in protective structures may cause severe injury to the persons or equipment it is supposed to protect. Previous research indicates that spalling occurs when and where the tensile strength of a strain-softening material like concrete is reached. By using a simple uni-axial numerical model, this study shows that spalling instead occurs when the cyclic response from a blast wave gradually increase the inelastic strains in the concrete. This means that spalling takes place after several loading cycles and not necessarily at the depth where tensile strength is firstly reached. Furthermore, the study shows that the cyclic response in the material model used for numerical simulation has a decisive influence on the position and extent of the resulting spalling crack.

In the second study the response of reinforced concrete structures subjected to blast loads was investigated. Numerical models are used to evaluate the numerical response of a simply supported reinforced concrete beam and a one-way supported slab with a combined damage and plasticity constitutive model for concrete, CDPM2. Previous research has shown that strain-rate de- pendent material parameters might be overestimated for higher strain rate. In this study, these features are evaluated for reinforced concrete structures where bending is the dominating response. The numerical analyses indicate that fracture energy during tensile fracture and how this value is chosen have larger effects on the deformations of the structure than whether or not the strain-rate dependency of the material properties are taken into account. It is also concluded that mesh size and modelling techniques may have a large impact on the resulting response of the structure in the numerical analysis.

Keywords: concrete, blast load, numerical modelling, spalling, stain-softening, wave propagation, transverse/reverse loading, dynamic response, cyclic crack propagation

to My Sources of Inspiration

Preface

The work on this thesis was carried out between August 2012 and July 2015 at the Department of Civil and Environmental Engineering, Division of Structural Engineering, Concrete Structures at Chalmers University of Technology. The work was performed within the research project entitled ”Blast and fragment impact: Reinforced and concrete and fibre concrete structures”. The research project is a continuation of earlier work on concrete structures subjected to severe dynamic loading conducted at Chalmers by Morgan Johansson, Joosef Leppänen and Ulrika Nyström. The project is financially sponsored by the Swedish Civil Contingencies Agency.

I would like to thank my supervisor and examiner, Associate Professor Mario Plos, for his support and guidance. I would also like to thank my assistant supervisors, Assistant Professor Rasmus Rempling, Adjuct Professor Morgan Johansson and Senior Lecturer Joosef Leppänen, for their invaluable input. Further, I would like to express my gratitude to MScEng Björn Ekengren, the Swedish Civil Contingencies Agency, for his persistent support and patience. I also want to thank Professor emeritus Kent Gylltoft, MScEng Rolf Dalenius, the Swedish Fortifications Agency, PhD Ulrika Nyström, VK Engineering and Professor Karin Lundgren for their valuable contributions to the work in the project group.

I want to thank all my colleagues who have contributed to my development as an engineer and as a researcher; especially Håkan Lantz and Carlos Gil Berrocal.

Finally, I thank my friends and family. I would not have reached this point without you.

Thesis

This thesis consists of an extended summary and the following appended papers:

Paper A J. Ekström, R. Rempling, and M. Plos. *Spalling in Concrete Subjected to Shock Wave Blast.* Submitted to "Engineering Structures"

Paper B J. Ekström, R. Rempling, M. Plos, and M. Johansson. *Finite Element Analyses of Concrete Structures Subjected to Blast Loads with a Damage-Plasticity based Material Model, CDPM2.* To be submitted for international journal

Author's contribution to jointly written papers

The appended papers were prepared in collaboration with the co-authors. In the following, the contribution of the author of this licentiate thesis to the appended papers is described.

Paper A Responsible for planning and writing the paper. Made numerical implementations and carried out numerical simulations.

Paper B Responsible for planning and writing the paper. Carried out the numerical simulations and the evaluation of the the results.

Other publications related to the thesis

In addition to the appended papers, the author of this thesis has also contributed to the following publications:

Ekström, J., Rempling, R., and Plos, M. (2014). "Influence of Strain Softening on Spalling of Concrete due to Blast Load". In: *Proceedings of the XXII Nordic Concrete Research Symposium*. Ed. by The Nordic Concrete Federation. Vol. 2/2014. 50. Reykjavik, Iceland: Norsk Betongforening, pp. 157–160.

Contents

Part I
Extended Summary

1 Introduction

1.1 Background

For decades the focus of civil defence has been on civil defence shelters to withstand the threat against warfare and to protect civilians. Latter years, the general focus has often shifted towards the protection of specific targets which host important functions to society. Direct attacks towards the civil population, such as terrorist attacks, also post a more common threat today than for a few years ago. Due to the rather rapid shift of area of interest, the general engineering community lack much of the knowledge and tools to design and evaluate structures with respect to dynamic events with very fast transient and high magnitude peak loads.

Most structural analysis approaches have been developed with different simplifications and approximations, because of limitations in knowledge and to restrict the extent of cases studied. When it comes to response of concrete structures due to highly dynamic events, the load due to an explosion and the general response of statically loaded concrete structures are relatively well-known. However, despite decades of research within the area, many phenomena involved for the dynamic response of reinforced concrete structures are not yet fully understood.

Numerical modelling of dynamic events has been more common in recent years and is to a large extent treated as an available complement to physical testing. Even so, the tools and techniques to evaluate structures with numerical models are in many respects unexplored. Since some phenomena are not fully understood, it becomes rather complicated to determine the needed properties of these numerical models.

1.2 Purpose, aim and objectives of research

The purpose of the research presented in this thesis is to study numerical approaches involving highly dynamic events towards reinforced concrete structures. In the long-run, the research intends to study how fibre concrete can be used in reinforced concrete structures to increase the ability of withstanding highly dynamic events, such as explosions within the civil community. In order to do so, understanding of the underlying phenomena during highly dynamic events when material fracture appears in concrete are prerequisite.

The aim of the research presented in this thesis is to study how dynamic responses of concrete structures subjected to highly intense blast loads can be modelled numerically. Both simplified models and more advanced numerical models were used to investigate some of the effects of different material properties of concrete and reinforced concrete structures. Furthermore, the aim was to relate material fractures in concrete to design methods that can increase the safety of concrete structures, both for new designs and to strengthen existing structures.

The objectives have been to evaluate numerical approaches based on a combined damage and plasticity model to describe the constitutive laws of concrete materials. Furthermore, to describe the influence of constitutive laws on the response of brittle materials, such as plain concrete, subjected to impulse loading with regards to spalling.

1.3 Scientific approach and methodology

The chosen scientific approach consists of literature reviews combined with theoretical modelling benchmarked with numerical models. The numerical models aim to provide a simplified approximation of real behaviours and, thus, support the knowledge creation of the underlying phenomena. Numerical models can be motivated by relatively low costs compared to experiments. They also provide the possibility of studying the course of event for any given sequence in time and to study responses which can be difficult to measure during experiments. By studying structural responses numerically, it is also possible to extract results that can be important in order to identify different properties of a real structure or specimen in an experiment.

The studies that were carried out in this thesis are in general based on constitutive models where concrete is represented by a combination of damage and plasticity. The choice to represent concrete during highly dynamic events through the use of a damage-plasticity model is a continuation of previous research at Chalmers the University of Technology, Nyström (2013), and the University of Glasgow, Grassl et al. (2013), and has been shown to successfully describe loading and unloading of concrete with large confinement effects and for the propagation of shock waves.

1.4 Scope and limitations

The thesis focuses on normal concrete and reinforced concrete. One of the studies investigates the development of spalling damage in a concrete wall and the influence of different material responses of the concrete during non-monotonic loading and unloading. The second study investigates the performance of the material model CDPM2, Grassl et al. (2013); Nyström (2013), which is a combined damage and plasticity model. Both studies are numerical studies. For the first study, investigating spalling, experimental data that can be used to verify the hypothesis have not been found. The second study, investigating the performance of CDPM2, is a numerical study of experiments designed and performed by other researchers. The tests were not designed to be primarily used to evaluate the response of a specific material model, but rather numerical models in general.

2 Loads due to blast and impact

2.1 Overview

Loads are usually divided into static loads, quasi static loads and dynamic loads based on the time duration of an action. However, dynamic loads span over a range of time intervals. Different time frames yield different types of responses, Gebbeken, Greulich, and a. Pietzsch (2001), both for the material response and the response of the whole structure and, thus, create different demands for the analytical routines and material representation.

Dynamic response can occur within different time frames. For example, when oscillation occurs in a structure, the time duration can be seconds or parts of seconds. During this time frame, the deformation of the structure changes and, thus, the internal and external forces for the structure change. If a moving object hits a structure, the response will depend on both the velocity and the material properties of the two bodies, Leppänen (2012). When a high velocity impact between a small object and e.g. a beam occurs, such as a fragment impact, local effects in the form of damage around the zone of impact will develop within a much shorter time interval than the global bending deformation of the beam.

When the type of loading condition is classified based on time intervals, a common measure used is the strain-rate caused at different martial points in the structure. By measuring the change in strains per time unit it is possible to separate long time intervals from short time intervals. In Figure 2.1 different engineering applications with regards to strain-rates are shown. The picture is taken from Nyström (2013) and is based on a variety of publications: Bischoff and Perry (1991); Field et al. (2004); Gebbeken and Ruppert (2000); Ramesh (2008); Zukas (2004). In this thesis responses of concrete structures due to blast waves from the detonation of explosives or the simulation of such event are studied. This corresponds to the "blast and impact" region in Figure 2.1.

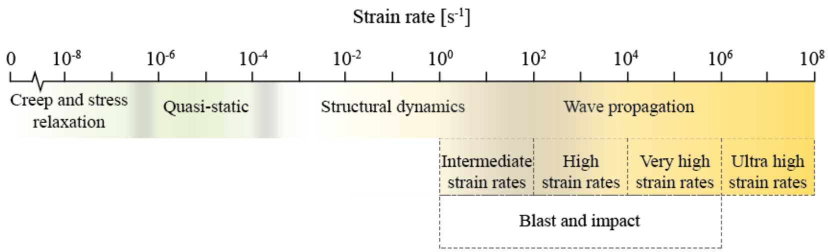


Figure 2.1: *Strain-rates and associated problem aspects taken from Nyström (2013)*

2.2 Blast wave in air

When a highly explosive substance detonates in the open air, a sudden release of energy occurs. An explosion can be characterised as a sudden volumetric expansion of matter due to physical or chemical change of state. The change of state results in a sudden release of potential energy to mechanical work. For a detonation of an explosive substance the expansion of gases creates an overpressure which generates mechanical work when the surrounding air is forced away. The highly compressed air surrounding the detonation creates a blast wave that propagates with super sonic speed from the epicentre of the explosion. Directly behind the front of the blast wave is a region where pressure, temperature, density and particle velocity are distinctly higher than the surrounding air. When the blast wave moves away, these properties rather rapidly return to their original states. For a fully developed blast wave, the pressure rises from the normal atmospheric pressure to a peak pressure more or less instantaneously. The time for the pressure to rise is therefore generally considered to be a singular jump in time. The pressure then decreases exponentially until an under-pressure is reached that returns to the original atmospheric pressure; see Figure 2.2. In structural analyses and evaluations, the blast wave is usually simplified and only the overpressure is considered. Thus, no negative pressure is applied to the structure. Furthermore, the exponential pressure decreases after the shock wave has reached the structure and can also be simplified to a linear decrease, Johansson (2012).

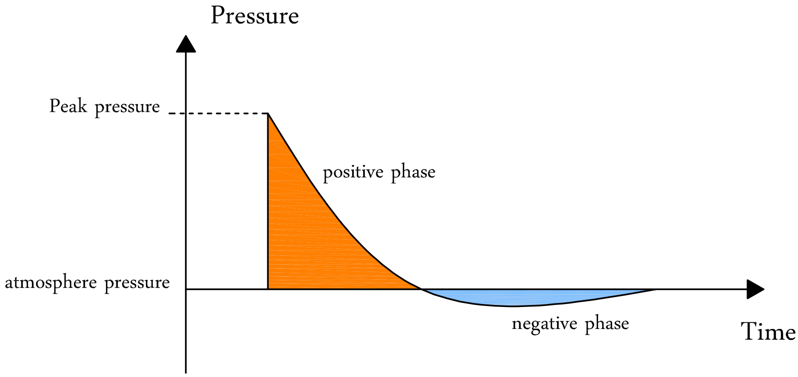


Figure 2.2: *Principal pressure-time relation for a blast wave in air*

2.3 Fragments

The detonation of a bomb will create not only a blast wave but will also send away fragments, Leppänen (2004). The detonation of the explosives will rip the casing of the bomb into small pieces creating a cluster of fragments, Janzon (1978). The fragments will represent mass and velocity and can add a substantial load to a structure. A blast wave and a cluster of fragments can reach a structure at different time intervals because of differences in which speed they travel, Nyström and Gylltoft (2009). Even though the actual impulse of a cluster of fragments might be distinctly smaller than from the blast wave, the damage to the surface of a structure can be substantial, Nyström and Gylltoft (2009). Furthermore, the damage to the surface may lead to a loss of capacity and a stiffness influencing the overall structural response. A study of the combination of fragments and blast wave showed a synergy effect, Nyström (2008). It was established that the combination of fragments and blast wave created a larger deformation than if the deformations due to the fragments alone were added to the deformation due to the blast wave.

An important difference between the stress response in a structure due to a blast load and a cluster of fragments is that the stress towards the surface of the structure is more or less independent of the properties of the structure for a blast wave. For the cluster of fragments, the material properties of the fragments and the material properties of the structure will affect the stress wave that will propagate through the structure after the impact. The velocity of the fragments will be important for the magnitude of the stress wave but the stiffness of the fragments as well as the stiffness of the material in the structure will also influence both the magnitude of the stress wave and the duration of the stress wave, Leppänen (2004); Leppänen (2012). The effect of the material properties of fragments can be indirectly studied by looking at the response of flyer plate impact tests, Grady (1996); Gebbeken, Greulich, and A. Pietzsch (2006); Riedel et al. (2008), where the material properties of the materials involved are used to calculate the material states.

3 Fracture due to blast and impact

3.1 Overview

A structure that experiences loading due to an explosion undergoes, in general, different reactions at various stages of the loading and unloading. The most obvious differences are responses related to local and global response, see Figure 3.1. However, for dynamic loading another important factor is the stress of the structure during different time intervals. Global failures can, in general, be determined based on the total energy or work applied to the structure from the load compared to the ability of the structure to absorb externally applied energy, Johansson and Laine (2012).

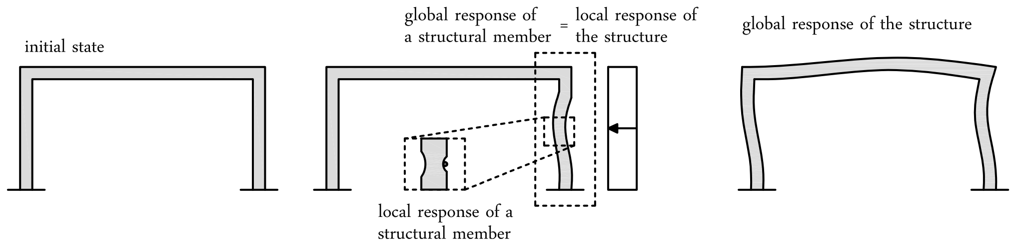


Figure 3.1: *Local and global response of a structure structural member and of an entire structure*

Other fractures are determined by stresses caused by the change in applied load over time, $\frac{\delta load}{\delta t}$, Meyers (1994). Thus, the total intensity of the load is not necessarily critical for initiating a failure process. If a certain load condition is critical for a specific fracture, the corresponding time interval when that fracture occurs has to be studied. The time frame for a local failure, such as spalling or scabbing, is shorter than for a global failure, such as a flexural failure or shear failure.

3.2 Description of failures and what can cause them

In the case of dynamic load conditions, different failures can occur in a structure compared to static load conditions. In the following section(s), the general conditions and related time intervals for different dynamic failures are presented. Dynamic failures are named differently in various literature. Here, the names of the fractures correspond to U.S. Army Corps of Engineers et al. (2008).

3.2.1 Spalling

When a wall or a slab is subjected to a highly intense blast wave or a high-speed object, such as a fragment or projectile, a compression wave may occur inside the structure. When a compression wave reaches the free edge at the back side of the structure a stress reflection occurs. This reflection can also be seen as a release wave due to the state of equilibrium; see Paper A. When a release wave starts to propagate back towards the loaded side of the structure, the stress state at the boundary will be zero. However, if the compression stress further into the structure has decreased due to the characteristic of the applied load, the release wave can create stress states made up of tensile stresses. If these tensile stresses are large enough they can result in a crack initiation in the structure, Mcvay (1988); Meyers (1994). If the applied load is intense enough, fragments of the structure can spall off at the back side of the structure which is not directly subjected to the load, see Figure. In a brittle material, such as concrete, spalling can occur more easily due to the large difference between compression and tensile capacity. In Paper A, spalling in concrete subjected to a shock wave blast was studied for a simplified one-dimensional specimen. It was shown that for certain cases of spalling, the cracks can develop during multiple cycles of stress waves rather than instantly as soon as the tensile strength is reached, which is generally argued by Mcvay (1988); Meyers (1994); Leppänen (2012). If this type of response is aimed at describing in numerical models, the constitutive laws describing the concrete become important with regards to non-monotonic crack propagation.

3.2.2 Scabbing

Spalling is generally associated with close-in detonation or clusters of fragments. A close-in detonation can create pressures strong enough to cause crushing and cratering on the loaded side of the concrete. Since the damage is caused by close-in detonation, the pressure confinement effects increase when the pressure propagates further into the structure but the pressure will also disperse when the wave propagates. Thus, the extension and depth of the cratering is usually limited.

3.2.3 Flexural and shear failures

The flexural response of a reinforced concrete structure subjected to dynamic loading is similar to the flexural response of a statically loaded structure. Failure modes are either crushing of the concrete or yielding of the reinforcement. Furthermore, different anchorage failures and support slipping can occur. Shear failure can occur in a similar manner as for statically loaded structures. However, for very intense loads shear failure can occur in earlier stages of the evolution of the deflections. When the load is first applied, a beam or a slab has a rigid body motion before the support forces develop. The internal forces in the structure occur first when the support forces appear. Thus, bending moments and shear forces emerge from the supports and propagate from there, Andersson and Karlsson (2012). Highly intense loads can therefore result in stresses on the structure closer to the supports compared to the same structure subjected to static loads. Direct shear, Krauthammer (2008), is a failure that may appear if the stresses in the structure are great early during the structural response.

4 Numerical analyses of failure in concrete structures

When a material like concrete is to be modelled through numerical analyses a number of approaches to describe material fracture are possible, such as, discrete crack models, non-local crack models and smeared crack models, Jirásek (2010). Any chosen approach has advantages and disadvantages. The work carried out in this thesis is based on a smeared crack approach where the properties of the inelastic deformations of concrete is smeared out over a band width. The material model studied in detail in this thesis was developed during a previous PhD project by Nyström (2013).

4.1 Essential properties of concrete constitutive models

Depending on the aim of a structural model and the loading condition, the demands on the utilized material models vary. When the response of, for instance, concrete is studied during static conditions, there are various aspects that need to be considered. Different stress states will yield different demands on the complexity of the material model. If a material model is simplified, it also, becomes more limited in terms of general applicability.

In dynamic response there are aspects of material response that are unique or of greater importance compared to static conditions. One of the unique properties, only implicitly considered in dynamics, is how the material strength depends on the rate of applied stress, generally measured as the strain-rate, $\frac{\delta \varepsilon}{\delta t}$. Other features which are less common in static evaluation include non-linear compaction under hydrostatic compression and residual strength after extensive material damage. These final two properties are more likely to occur in fast dynamic events because of inertia effects creating local confinements during very short time intervals. There are many different approaches to describe these responses with the help of a constitutive model. This thesis is a continuation of a previous project where a combined damage and plasticity model was developed in order to describe these properties, Nyström (2013); Grassl et al. (2013). The evaluation of properties is presented in Nyström (2013) and in Figure 4.1 where the most important features of a material model describing concrete are placed at the base of the pyramid and in decreasing importance towards the top.

In Nyström (2013) strain rate dependency of strength, post-peak softening, non-linear compaction curve for high pressures and residual strength in confined compression were concluded to be the most important features of the response of concrete for dynamic loads. Post-peak softening is a material property which is not unique to dynamic conditions. For multi-axial loading, pressure-sensitive strength is also considered to be a very general property of concrete.

Strain-rate dependent strength, however, is an effect which only impacts the mate-

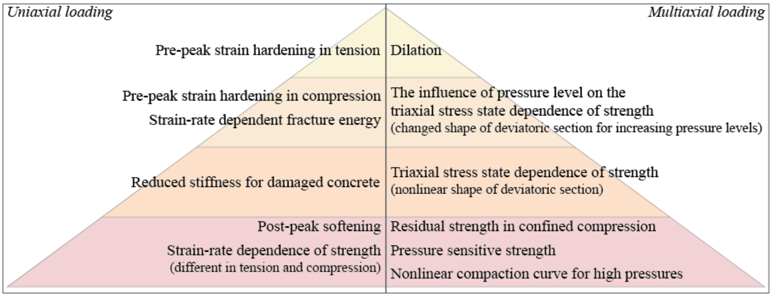


Figure 4.1: *Assessment of properties during development of material model, from Nyström (2013)*

rial properties during dynamic conditions. The dynamic tensile strength has been shown to be as high as eight times the tensile strength for a static load condition, Malvar and Ross (1998). In compression, the observed dynamic strength is about 2,5 times the static strength, Bischoff and Perry (1991).

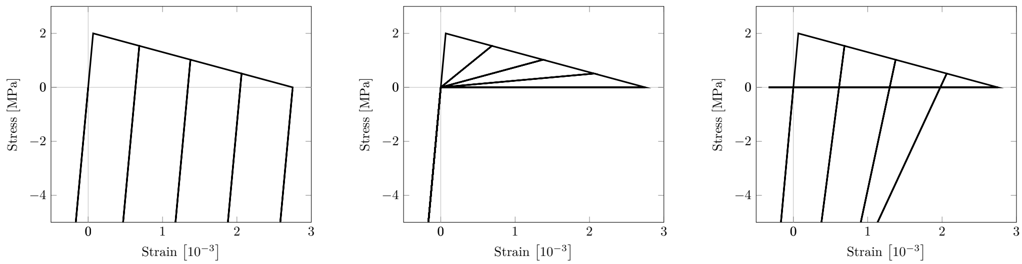
Residual strength in confined compression and the non-linear compaction curve for high confinement pressure, Williams et al. (2006), are aspects of the response which occur both during dynamic and static conditions. However, high confinement pressures are difficult to create and maintain during static conditions since the confinement requires externally applied loads. For dynamics, the confinement can be created due to inertia effects in the material where a high pressure is confined by the surrounding material.

4.2 Constitutive models for concrete fracture in tension

Concrete, with its very different properties depending on the stress state, needs rather complex constitutive laws to capture the response for an arbitrary stress state. In many applications, the focus lies on the ability to capture a specific response, which allows for reducing the complexity of the material model.

If a concrete specimen is loaded in monotonic tension under static condition, the tensile stress will reach a peak value from which the stress gradually decreases with increasing deformation. This material softening develops more or less exponentially but in most applications, it is considered sufficient to use a bi-linear softening law, Gylltoft (1983), or even a linear softening law.

In Paper A, spalling in a concrete wall subjected to a close-by explosion is studied. In this paper, the tensile response of the concrete is modelled according to three different constitutive laws, a plasticity model, a damage model and a combined damage and plasticity model. All of them use a linear softening when cracks are developed in the concrete. When a crack is forming, even though the stress-strain response is similar, the structural response becomes different. A plasticity model and a damage model can describe the same type of softening in the material. However, in a plasticity model, the elastic response upon unloading will be based on the original stiffness of the material whereas, for a damage model, the stiffness will be reduced. This means that the final structural response can differ if, e.g., a non-monotonic response takes place, as shown in Paper A. Since the concrete undergoes multiple stages of compression and tension, see Figure 4.2, the response during the transition will affect the result.



(a) *Plasticity* (b) *Damage* (c) *Damage-Plasticity*

Figure 4.2: *Stress-strain relation for cyclic tensile and compressive loading of concrete for (a) aplasticity model (b) a damage model (c) a damage-plasticity model*

4.3 Evaluation of CDPM2

One of the aims of this study has been to evaluate and confirm the potential areas of development for the new material model CDPM2 when used in dynamic models and to identify possible areas of improvements. In Nyström (2013), the following features were suggested as potential areas of improvement:

- Increased material stiffness after non-linear compaction
- Avoiding of overestimated fracture energy due to double strain-rate dependency
- Reduction of the strain-rate dependency for compressive strength for modelling with solid elements at high strain-rates

The aim was to study these features in Paper B. The conclusions from the study is summarised below:

Increased material stiffness after non-linear compaction

The constitutive laws for CDPM2 do not affect the material stiffness after volumetric compaction, i.e., when the concrete is compressed in a way so that the pore system collapses and a more solid material is created. This feature of the concrete material is relevant when a structure is hit by a high speed projectile or fragment. It was shown in Nyström (2013) that CDPM2 had too low a stiffness for hydrostatic pressures of 2 GPa and higher. In Paper B structures subjected to blast loads resulted in flexural deflections was studied and for that type of response, such high pressures were not reached.

Avoiding of overestimated fracture energy due to double strain rate dependency

The constitutive laws that treat the tensile strength and the strain softening branch in tension results in an increased tensile strength and an equally increase of the maximum crack opening when zero stress is reached, see Nyström (2013) and Paper B. Since both the strength and the strain that represent the maximum crack opening are increased, the dynamic increase factor for the fracture energy, DIF_{G_F}, is equal to the dynamic increase factor for the strength squared, $DIF^2_{f_{ct}}$. The available studies of how the strain-rate influence the fracture energy are limited but indicate that the dynamic increase factor for fracture energy is proportional to the rate effect on the tensile strength, Weerheijm and Van Doormaal (2007). In Weerheijm and Van Doormaal (2007), it is also concluded that the maximum crack opening remain constant. The study in Paper B shows that a variation of input values for the fracture energy results in a large variation of deflection for beams and plates. Therefore, an overestimation of the strain-rate effect for the fracture energy can be expected to result in an underestimation of deformation similar to those seen in Paper B.

Reduction of the strain rate dependency for compressive strength for modelling with solid elements at high strain rates

The strain-rate dependency of the material strength is, in CDPM2, treated by using a magnification factor for the concrete strength based on the strain rate of the total strain, Nyström (2013). For tension, the rate factor is based on the expression proposed by Malvar and Ross (1998) and for compression, the expression proposed in *fib Model Code for Concrete Structures 2010* (2013) is used. However, in Nyström (2013), it was shown that the expression proposed in *fib Model Code for Concrete Structures 2010* (2013), combined with 3D continuum elements, resulted in an overestimation of the rate effects for the compression strength. Paper B studied the flexural response of a beam and a plate with and without the strain rate effect turned on for CDPM2. It was shown that the strain rate effect has a significant influence on the deflection of the structure. However, how much of that effect that comes from the overestimation of compression strength and how much that comes from the overestimation of the fracture energy could not be determined in the study. However, to treat the element size dependency affecting the compression strength, shown in Nyström (2013), the expression used to describe the strain rate dependent compression strength should be updated so that the inertia effects are omitted from the constitutive laws for 3D continuum elements.

Strain softening for compression failure

Concrete failure in uniaxial compression is reached after a softening, Karsan and Jirsan (1969). In a smeared crack approach, the localisation zone where the inelastic deformation takes place needs to be defined in order to obtain a correct stress-strain relation, Jirásek (2010). The implementation of CDPM2 defines a stress-strain relation based on a pre-specified element size, and the ductility measure, Grassl et al. (2013). In Paper B, problems with convergence occurred for the slab analyses. It was believed to be due to the description of the softening in compression. To treat this, elastic elements were used at the concrete surface by the supports and at the top of the slab where the plastic hinge occurred.

5 Conclusions

Two studies have been presented in this theses. The first in Paper A, where spalling in a concrete specimen due to a blast wave was studied. The assumption that the damage due to the tensile stress from the release wave develops instantaneous within a time singularity was shown to be inaccurate. During the development of the fracture, e.i. the crack propagation, the release wave continued to propagate past the point of first crack initiation. In the studied case where the length of the blast wave was much longer than the studied concrete specimen, the crack did not form until multiple compression and release waves had passed. It was also shown that the choice of constitutive model to describe the tensile fracture affected the response and the propagation of blast wave. It is therefore concluded that for some case of spalling, the choice of constitutive model for concrete tensile fracture can be crucial.

In the second study, presented in Paper B, the performance of the new material model, CDPM2, based on combined damage and plasticity, was investigated for blast loaded beam and slab specimens. Some of the limitations presented in Nyström (2013) and how they affected the response of beams and slabs were investigated. It was concluded that the strain rate dependency of strength and fracture energy of the concrete affected the response of the structures. It was also shown that the chosen fracture energy influenced the deflection of the structures more than if strain-rate dependent strength was included for the concrete. Thus, it was concluded that the strain-rate dependency of the fracture energy must be described correctly. The available research with regard to strain rate dependency for the fracture energy, Weerheijm and Van Doormaal (2007); Schuler et al. (2006), suggested a lower increase of fracture energy due to increased strain-rates compared to tensile strength. The constitutive laws in CDPM2 should, thus, be adjusted to better fit available data.

Finally, in Paper B, convergence problems occurred in areas of large compression and to some extent distortion for the slab analyses, e.i. around the support and at the top of the slab. To treat this in the study, elastic elements were used in the outer layer of the slab in these areas, see Paper B. It was assumed that the convergence problems were due to the description of the strain softening for CDPM2 in compression and that the concrete showed a too brittle behaviour. Therefore, the localisation length should be possible to define for an analysis in the same way as for tensile fracture.

References

Andersson, S. and Karlsson, H. (2012). “Structural response of reinforced concrete beams subjected to explosions: Time dependent transformation factors, support reactions and distribution of section forces”. Master Thesis. Chalmers University of Technology, p. 145.

Bischoff, P. H. and Perry, S. H. (Nov. 1991). “Compressive behaviour of concrete at high strain rates”. In: *Materials and Structures* 24.6, pp. 425–450. ISSN: 0025-5432. DOI: 10.1007/BF02472016.

Ekström, J., Rempling, R., and Plos, M. *Spalling in Concrete Subjected to Shock Wave Blast*. Submitted to ”Engineering Structures”.

Ekström, J., Rempling, R., Plos, M., and Johansson, M. *Finite Element Analyses of Concrete Structures Subjected to Blast Loads with a Damage-Plasticity based Material Model, CDPM2*. To be submitted for international journal.

fib Model Code for Concrete Structures 2010 (Oct. 2013). Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA. ISBN: 9783433604090. DOI: 10.1002/9783433604090.

Field, J. E., Walley, S. M., Proud, W. G., Goldrein, H. T., and Siviour, C. R. (2004). “Review of experimental techniques for high rate deformation and shock studies”. In: *International Journal of Impact Engineering*. Vol. 30. 7, pp. 725–775. ISBN: 0734-743X. DOI: 10.1016/j.ijimpeng.2004.03.005.

Gebbeken, N., Greulich, S., and Pietzsch, A. (Dec. 2006). “Hugoniot properties for concrete determined by full-scale detonation experiments and flyer-plate-impact tests”. In: *International Journal of Impact Engineering* 32.12, pp. 2017–2031. ISSN: 0734743X. DOI: 10.1016/j.ijimpeng.2005.08.003.

Gebbeken, N., Greulich, S., and Pietzsch, a. (2001). “Performance of Concrete Based Building Materials Against Blast and Impact 1 Introduction”. In: JANUARY.

Gebbeken, N. and Ruppert, M. (2000). “A new material model for concrete in high-dynamic hydrocode simulations”. In: 70.March 1999.

Grady, D. (1996). “Shock Equation of State Properties of Concrete”. In: *International conference on structures under shock and . . .* Pp. 1–10.

Grassl, P., Xenos, D., Nyström, U., Rempling, R., and Gylltoft, K. (Nov. 2013). “CDPM2: A damage-plasticity approach to modelling the failure of concrete”. In: *International Journal of Solids and Structures* 50.24, pp. 3805–3816. ISSN: 00207683. DOI: 10.1016/j.ijsolstr.2013.07.008.

Gylltoft, K. (1983). “Fracture mechanics models for fatigue in concrete structures”. PhD thesis. LuleåUniversity of Technology, Sweden, p. 210.

Janzon, B. (1978). *Grundläggande stridsdelsfysik*. Tech. rep. Stockholm, Sweden, p. 164.

Jirásek, M. (2010). *Modeling of Localized Inelastic Deformation*. 7th ed. Czech Technical University, Prague.

Johansson, M. (2012). *Luftstötvåg*. Karlstad, Sweden: Myndigheten för samhällsskydd och beredskap, p. 61. ISBN: 9789173832656.

Johansson, M. and Laine, L. (2012). *Bebyggelsens motståndsförmåga mot extrem dynamisk belastning, Del 3 – Kapacitet hos byggnader*. Karlstad, Sweden: Myndigheten för samhällsskydd och beredskap, p. 100.

Karsan, I. D. and Jirsan, J. O. (1969). “Behavior of Concrete Under Compressive Loadings”. In: *Journal of the Structural Division* 95.ST12, pp. 2543–2563.

Krauthammer, T. (2008). *Modern Protective Structures*. Civil and environmental engineering. Taylor & Francis. ISBN: 9781420015423.

Leppänen, J. (2004). *Concrete Structures Subjected to Fragment Impacts*. ISBN: 9172915110.

— (2012). *Splitterverkan*. Karlstad, Sweden: Myndigheten för samhällsskydd och beredskap, p. 134. ISBN: 9789173831888.

Malvar, L. J. and Ross, C. (1998). “Review of Strain Rate Effects for Concrete in Tension”. In: *ACI Materials Journal* 95.6. ISSN: 0889-325X. DOI: 10.14359/418.

Mcvay, M. K. (1988). *Spall Damage of Concrete Structures*. Tech. rep. Vicksburg, Mississippi: Structures Laboratory, Department of the Army, Waterways Experiment Station, Corps of Engineers, p. 175.

Meyers, M. A. (1994). *Dynamic Behavior of Materials*. Wiley-Interscience publication. New York , NY: John Wiley & Sons, Inc. ISBN: 9780471582625.

Nyström, U. (2008). “Concrete structures subjected to blast and fragment impacts : numerical simulations of reinforced and fibre-reinforced concrete”. Licentiate Thesis. Chalmers University of Technology, Göteborg, Sweden, p. 72.

— (2013). “Modelling of Concrete Structures Subjected to Blast and Fragment Loading”. PhD thesis. Chalmers University of Technology, Göteborg, Sweden, p. 83. ISBN: 9789173858052.

Nyström, U. and Gylltoft, K. (Aug. 2009). “Numerical studies of the combined effects of blast and fragment loading”. In: *International Journal of Impact Engineering* 36.8, pp. 995–1005. ISSN: 0734743X. DOI: 10.1016/j.ijimpeng.2009.02.008.

Ramesh, K. (2008). “High rates and impact experiments”. In: *Springer handbook of experimental solid mechanics*. New York , NY, USA: Springer, pp. 929–959.

Riedel, W., Wicklein, M., and Thoma, K. (Mar. 2008). “Shock properties of conventional and high strength concrete: Experimental and mesomechanical analysis”. In: *International Journal of Impact Engineering* 35.3, pp. 155–171. ISSN: 0734743X. DOI: 10.1016/j.ijimpeng.2007.02.001.

Schuler, H., Mayrhofer, C., and Thoma, K. (Oct. 2006). “Spall experiments for the measurement of the tensile strength and fracture energy of concrete at high strain rates”. In: *International Journal of Impact Engineering* 32.10, pp. 1635–1650. ISSN: 0734743X. DOI: 10.1016/j.ijimpeng.2005.01.010.

U.S. Army Corps of Engineers, Naval Facilities Engineering Command, and Air Force Civil Engineer Support Agency (Apr. 2008). *UFC 3-340-02 Structures to Resist the Effects of Accidental Explosions*. Tech. rep. May 2005, p. 1867.

Weerheijm, J. and Van Doormaal, J. (Mar. 2007). “Tensile failure of concrete at high loading rates: New test data on strength and fracture energy from instrumented spalling tests”. In: *International Journal of Impact Engineering* 34.3, pp. 609–626. ISSN: 0734743X. DOI: 10.1016/j.ijimpeng.2006.01.005.

Williams, E., Akers, S. a., and Reed, P. a. (2006). “Laboratory Characterization of SAM-35 Concrete Geotechnical and Structures”. In: September.

Zukas, J. (2004). *Introduction to Hydrocodes*. Studies in Applied Mechanics. Elsevier Science. ISBN: 9780080535012.