Influence of strain softening on spalling of concrete due to blast load

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ABSTRACT

A society needs a certain readiness for different emergency situations, such as explosions within the urban community but also civil safety shelter in the case of war. Therefore, the ability to evaluate and to strengthen existing buildings exposed to new demands is of great importance. Many experiments and numerical analyses indicate that structures of fibre reinforced concrete yield a more favourable response during dynamic load conditions compared to plain concrete. In this study the effects of spalling of a concrete wall subjected to blast loads were studied for plain concrete modelled with an elastic-plastic material model. The results from the analysis show that spalling occur when cyclic loading from a pressure wave gradually increase the plastic strains in the concrete.

**Key words:** wave propagation, strain-softening, concrete, spalling

1. INTRODUCTION

In society there is a certain need of readiness for different emergency situations, such as unprovoked explosions within the urban community or even in case of act of war. In these situations, important buildings, and especially civil safety shelters are fundamental for the readiness. In Sweden, the building stock is ageing and the focus lies upon maintaining existing buildings rather than demolishing and rebuilding. Therefore, the ability to evaluate and to strengthen existing buildings exposed to new demands is of great importance. In an on-going research programme at Chalmers University of Technology, financed by the Swedish Contingency Agency, MSB, structural behaviour of concrete structures subjected to blast and fragment loading is studied. The current project is focusing on the behaviour of fibre reinforced concrete with and without main reinforcement bars.

During shock dynamics - such as blast and impact loading - the time frame where the structural response takes place is relatively short. In structural evaluation related to static condition, the time frame from unloaded structure to fully loaded structure can span over a few seconds, short term load, and up to hours or years, intermediate and long term load. For shock dynamics the time duration from the load origin to the peak stress of the structure can be as short as a fraction of a millisecond. During this time span the structural response can be very different compared to

a static load case. Fracture modes which never occur for a static load can turn out to be the most critical response. However, both in static and in dynamic response similar structural properties and material properties are considered as favourable.

For a structure subjected to high dynamic loads, such as explosions or impacts, a high ductility of the structure is usually considered as favourable, (Johansson & Laine 2012). The argument for this is that a high ability to withstand large deformations can give the structure a good ability to absorb the high energy content of the load. Regarding concrete structures, fibre reinforced concrete is a material that can be designed to have a high ductility during fracture of the material, compared to plain concrete. For this reason it is generally argued that fibre reinforced concrete provides an increased ability to withstand high dynamic loads when used in a structure, compared to a structure designed with plain concrete. Many experiments and numerical analyses indicate that structures of fibre reinforced concrete have a higher resistance against damage propagation in the structures with regard to damage critical for the internal function of persons, such as thrown pieces of concrete into the interior of the protective structure, (Foglar & Kovar, 2013); this phenomenon is called spalling of concrete.

In order to protect the inhabitants of a building or a shelter it is important that the material do not spall. Spalling can occur when a compression wave reaches a free surface from where a release wave will start to propagate in the opposite direction, (McVay 1988). The gradient between applied load and the time duration will create a tensile stress when the release wave propagates back in the structure, see Figure 1. If the tensile stress reaches the tensile capacity the damage, which can lead to spalling, will be initiated. However, a fully open crack where no tensile stress can be transferred between the two sides will not occur instantaneously. For brittle material with a much higher resistance against compressive stresses than tensile stresses, such as concrete, spalling occurs in a higher extent than for instance for metals.
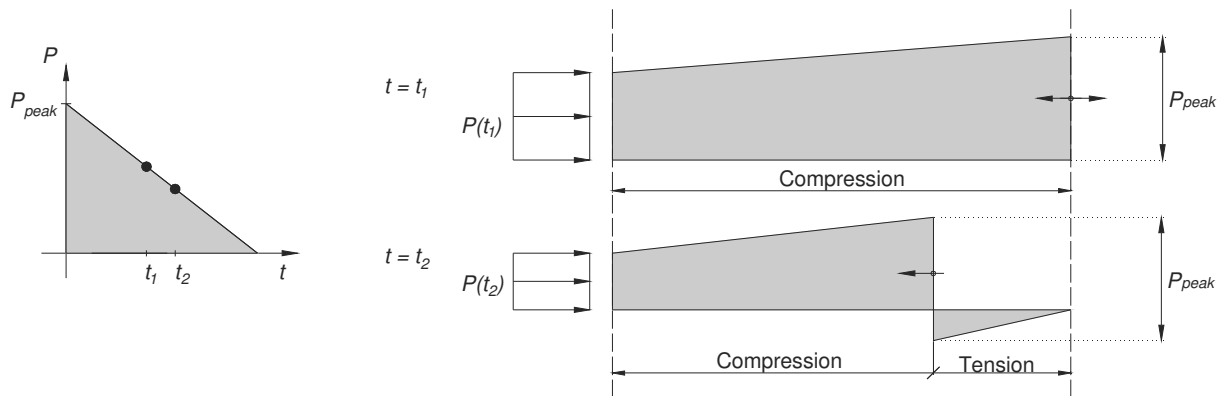
Figure 1   Stress distribution when a compression wave reaches the free edge (above), and when crack initiation occurs due to release wave (below).

Numerical models can be a powerful tool to understand the behaviour of a structure subjected to high dynamic loads. Different parameters of the load and the geometry can be evaluated and the structural behaviour can be studied from the time the load is applied until the final state of the structural response. As comparison, for experimental studies, the final stage of the response is usually the only state which can be studied in detail.

The aim of this study is to better understand the phenomena of spalling in plain concrete and fibre reinforced concrete. Furthermore, focus is set on how a finite element model with smeared crack approach and homogenous material response behaves when the increased ductility in tension of fibre concrete is modelled using a modified strain softening law. The effect of

spalling in a concrete wall subjected to blast loads was studied for plain and fibre reinforced concrete. A semi-analytic approach was used to understand the phenomena of spalling in concrete, crack propagation during spalling, the effects with regards to different concrete materials and the limitations and abilities of a finite element model which experiences spalling damages.

2. METHOD

Wave propagation in a plain concrete wall element was studied with the simplified theoretical approach by a 1-dimensional rod. The applied load was simplified to a plain pressure wave with linear decrease of the pressure after peak pressure, see Figure 2. The load was chosen such as spalling is achieved, both in the simplified theoretical approach, (McVay 1988) , and for the numerical model. The load corresponds to a hemispheric charge of 1500 kg TNT at a distance of 5 m calculated according to (ConWep 1992). The concrete is considered as an elastic-plastic material with a weak discontinuity to describe the crack localization. The softening law is defined to resemble plain concrete. For plain concrete a linear softening law is used. The stress-strain relation to describe the softening branch is smeared out over a fracture zone equal to 3 times the maximum aggregate size, (Weerheijm & Van Doormaal 2007). With assumed maximum gravel size of 16 mm the crack band width becomes 48 mm. Yielding only occurs for tension when the tensile capacity is reached. Unloading and compression of elements will be elastic for any state. The fracture energy is calculated according to (fib Model Code 2010). The structural model is a spring and mass model with proportional stiffness damping based on the linear elastic stiffness matrix. The analysis is carried out with non-linear explicit analyses in MATLAB®. The numerical model and input for model geometry, material model and external load applied on the structure are presented in Figure 2.

L = 300 mm A = 1 mm^2

E = 30 GPa   = 2.35 kg/dm^3
f_{ct} = 2.0 MPa G_F = 132 N/m

$F(t) = A \cdot P(t)$

Number of elements N = 100

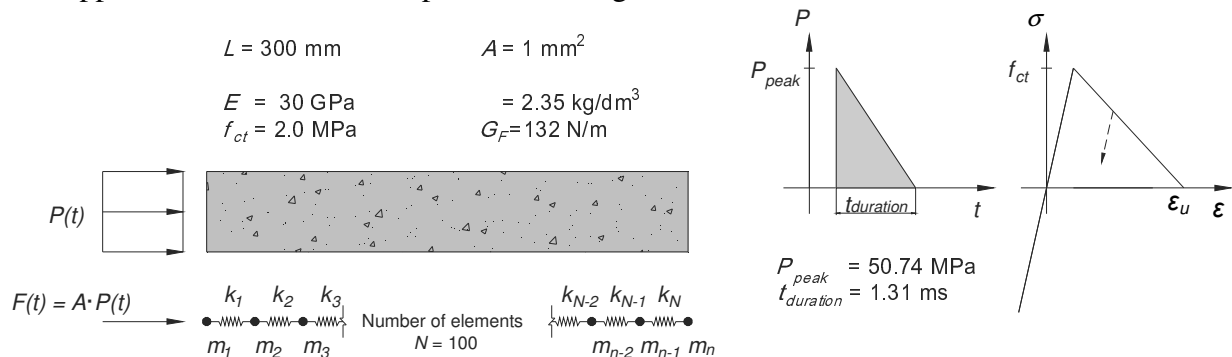P_{peak} = 50.74 MPa
$t_{duration}$ = 1.31 ms

Figure 2 – Studied wall segment, numerical model, applied load and material response.

3. RESULTS

The plastic strains from the numerical analysis are presented in time steps of $\Delta t = 2L/c$. Thus, during one time step, a stress wave can travel the distance of twice the wall thickness. In the theoretical model spalling occurs during the first cycle when the release wave travels back towards the left side of the wall, i.e. $\Delta t/2 < t < \Delta t$. With the analysed wall and the applied load the first spalling crack occurs 92 mm from the right side with the theoretical approach presented in (McVay 1988). Because of the load duration and the linear decrease of pressure additionally spalling cracks should be able to form each 92 mm. In the numerical analysis the crack initiation during the first cycle occurs 97 mm from the right side of the wall. However, the growth of the plastic strain is small in this element. When the release wave propagates back towards the left side a higher plastic strain is reached in the following elements. The development of the plastic strain stops when the second compression wave propagates from the left side of the wall towards the right side. During the second release wave the plastic strain grows a bit

more. For each cycle a higher maximum plastic strain is reached and the strain localizes to a few elements, see Figure 3a. The stress-strain relation of the material point where the highest plastic strain is attained is presented in Figure 3b. This point corresponds to $x = 167$ mm and the stress-strain response shows the cycles for which the plastic strains gradually increases.
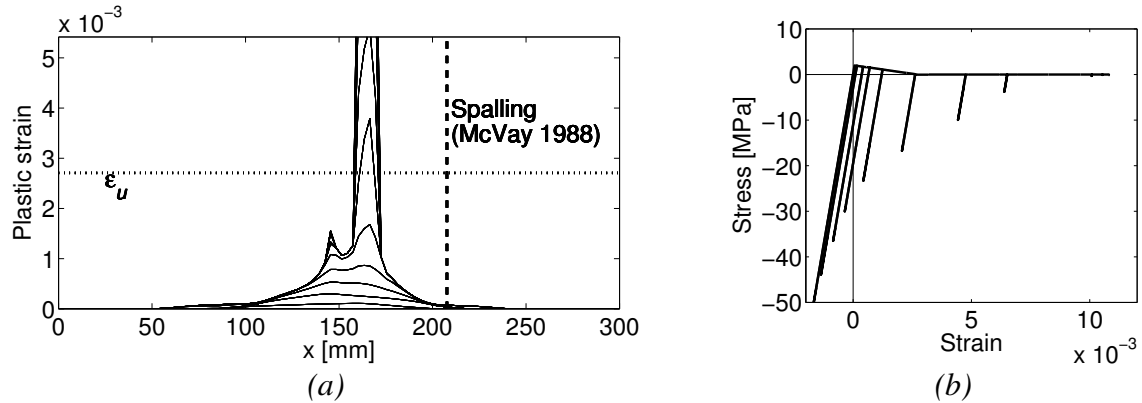

Figure 3   *(a) Distribution of plastic strain during different time steps Δt, and (b) stress strain response in the strain localization zone.*

4. DISCUSSION

When the tensile strength of a material and the material softening is taken into account the damage propagation which leads to spalling will be different compared to an approach where a crack is considered as fully developed as soon as the tensile strength is reached. According to the numerical analysis, with elastic-plastic material, spalling occurs after cyclic development of the plastic strain. The load duration, i.e. the pressure-time gradient, affects the number of cycles needed to develop the final strain localization. Continuation of the study will include the effects of spalling when a damage model is used and the effects of fibre concrete modelled with increased ductility of the softening branch in tension.

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