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Spalling in concrete subjected to shock wave blast

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ABSTRACT

This paper studies the response in a concrete wall subjected to shock wave blast, leading to spalling failure. 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. Many theoretical expressions indicates that spalling occurs when and where the tensile strength of a strain-softening material like concrete is reached regardless of the time duration of the applied load. By using a simple uni-axial numerical model, this study shows that spalling instead might 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.

1. Introduction

1.1. Background

In society, there is a certain need of preparedness for different emergency situations, such as unprovoked explosions within the urban community or acts of war. In these situations, important buildings, such as civil defence shelters and protective structures are fundamental to our readiness. In Sweden, the building stock is ageing and the focus is upon maintaining existing buildings rather than demolishing and rebuilding them. Therefore, the ability to evaluate and strengthen existing buildings exposed to new demands is of major importance.

A structure can experience different types of load effects depending on the size and position of an explosion. During shock dynamics – such as blast and impact loading – the time frame during which the structural response takes place is relatively brief. In structural evaluations related to static conditions, the time frame from unloaded structure to fully loaded structure can span over a few seconds, i.e. short term load, and up to hours or years, i.e. 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 brief as a fraction of a millisecond [1,2]. During this time span, the structural response differs greatly from a static load case and evaluation procedures used for static conditions are in many cases invalid [3]. Fracture modes which never occur for a static load can turn out to be the most critical response [4,5]. However, in both static and dynamic response, similar structural and material properties are considered favourable, such as increased ductility, both in terms of structural response [6] and material response. The rationale for this is that a high ability to withstand large deformations can give the structure a fine ability to redistribute forces and for dynamic loads to absorb the high energy content of the load as well.

Concrete is a material which undergoes softening during fracture, both in compression [7] and in tension [8]. A common way by which the ductility may be increased, compared to plain concrete, is to add fibres so that the energy dissipation during fracture of the material increases [9]. For this reason, it may be argued that fibre reinforced concrete, when used in structures, provides an increased ability to withstand high dynamic loads compared to a structure designed with plain concrete. Many experiments and numerical analyses [10–13] indicates that structures of fibre reinforced concrete have a higher resistance to damage critical to the internal function of individuals, such as pieces of concrete thrown into the interior of the protective structure. The latter phenomena of concrete failure, with cracks parallel to the surface, is called spalling [14–16].

Numerical models can be powerful tools to understand the behaviour of a structure subjected to high dynamic loads. Different parameters of the load, the geometry and the material can be

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evaluated and the structural behaviour can be studied from the time the load is applied until the final state of the structural response. For comparison, for experimental studies the final stage of the response is usually the only state which can be studied in detail. Hence, by modelling experiments, a better understanding of the entire response sequence can be achieved.

1.2. Problem identification

In order to protect the inhabitants of a building from an explosion, it is important for the material not to spall when subjected to a blast or fragment load. Spalling can occur when a compression wave with a negative pressure–time gradient reaches a free surface from where a release wave will start to propagate in the opposite direction [14–16]. The pressure–time gradient of the applied load will cause a tensile stress when the release wave propagates back into the structure. If the tensile stress were to reach the tensile capacity, damage would be initiated. Many studies, where analytical expressions for spalling are derived, have assumed that spalling occurs when the tensile capacity is reached, e.g. [14,15]. The stress state in a wall where a plain pressure wave with a linearly decreasing pressure has propagated to the unloaded side is illustrated in Fig. 1. In the same figure, the stress state is shown when the release wave that propagates back towards the loaded side has reached a point where a tensile stress equal to the tensile strength has been reached.

The approach assumes that a fully open crack in the material is created during the stress–time singularity which defines the pressure and release waves when the tensile capacity is reached. The assumption that a fully opened crack can be created during this singularity was supported in a study of wave propagation in strain-softening materials [17]. However, for a strain-softening material the momentary drop in tensile stress in the crack means that the deformation discontinuity, i.e. the crack, is created during a time singularity. Thus, the energy within the stress wave must be infinite. Since the pressure peak and, thereby, energy of the pressure wave is finite, the crack cannot open during the time singularity. In fact, a crack can only be initiated during the singularity but the crack can only develop during the time after the wave has passed the material point. To achieve the response described in [14,15], the crack initiation and the development of the crack needs to be neglected. Therefore, this approach cannot consider the effects of the material ductility. Instead, using this approach, varying ductility of the material will predict the same response. Thus, a design using a more ductile material, such as fibre reinforced concrete, will not be favourable compared to a brittle material, such as ordinary plain concrete, if the material were to undergo strain softening. However, this is in general not the conclusion from experiments where structures with fibre concrete experience less damage compared to the same structure with plain concrete [10,12].

1.3. Aim and objectives

The aim of the study was to present how material mechanisms influence the crack propagation in brittle material subjected to an impulse load which result in spalling damages. The objectives were to:

- identify the general response of crack-softening materials, such as concrete, with regard to crack propagation during spalling attributable to impulse loading,
- investigate the effect of material strength and crack-softening during the fracture process in brittle crack-softening materials according to the brittle crack spalling approach described in [14,15],
- present the effects of using a plasticity model, a damage model, and a combined damage and plasticity model to describe the material response of spalling concrete,
- identify important properties of the constitutive models used to represent a material which aims to describe spalling phenomena in brittle materials such as concrete.

1.4. Method

The analytical solution to crack initiation for spalling damage in a crack-softening material was studied for a one-dimensional wave propagation. The effect of including the crack-softening, i.e., the fracture energy was investigated, thus, the fracture was not allowed to emerge within a defined singularity. Furthermore, the crack-softening influences on crack propagation and the development of stress waves in the structure were studied with the help of this approach.

A one-dimensional numerical model for uniaxial response was developed to study the effect of strain localisation and the nonlinear non-monotonic material response for a section of a concrete wall subjected to blast waves. Different types of models were used to represent the softening of the material and to study the importance of choosing a correct representation of the non-monotonic material response during crack-softening. The crack-softening was represented by a strain-softening approach [18]. The crack propagation and the position of the fully open crack were compared to the predicted response using the simplified approach for brittle crack spalling according to [14].

1.5. Limitations

In this paper, the conceptual differences between a brittle crack approach and a strain-softening crack approach for the modelling

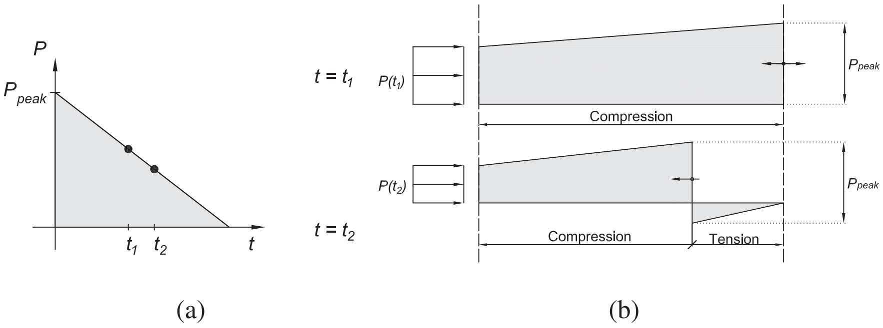

Fig. 1. Illustration of (a) the applied pressure wave towards the left edge of the wall and (b) the stress distribution through the thickness of the wall when the pressure wave reaches the unloaded right edge of the wall (above) and at crack initiation (below).