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On the numerical modelling of bond for the failure analysis of reinforced concrete

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ABSTRACT

The structural performance of reinforced concrete relies heavily on the bond between reinforcement and concrete. In nonlinear finite element analyses, bond is either modelled by merged, also called perfect bond, or coincident with slip, also called bond-slip, approaches. Here, the performance of these two approaches for the modelling of failure of reinforced concrete was investigated using a damage-plasticity constitutive model in LS-DYNA. Firstly, the influence of element size on the response of tension-stiffening analyses with the two modelling approaches was investigated. Then, the results of the two approaches were compared for plain and fibre reinforced tension stiffening and a drop weight impact test. It was shown that only the coincident with slip approach provided mesh insensitive results. However, both approaches were capable of reproducing the overall response of the experiments in the form of load and displacements satisfactorily for the meshes used.

1. Introduction

Ductile, durable and cost effective reinforced concrete structures can be produced by designing the reinforcement arrangement and bond properties between reinforcement and matrix. The nonlinear finite element method has the potential to support the design process of reinforced concrete structures, because it is capable of producing detailed results which are difficult to extract from physical experiments. By analysing the nonlinear response of individual components, namely plain concrete, reinforcing steel and the interaction of reinforcement and concrete, detailed information about the composite response can be obtained. This requires modelling techniques, which provide a realistic description of the mechanical response of individual components. For a successful application of the nonlinear finite element method, the models need to be robust, based on input parameters which can be easily obtained and produce results independent of numerical approximation procedures, i.e. independent of mesh and step size.

For the nonlinear finite element method, one common check is to show that the results are mesh-insensitive. For plain concrete, this is a challenging task since the response in tension and low confined compression is quasi-brittle which is characterised by strain softening, i.e. decreasing stress with increasing strain. This strain softening results in localised deformation patterns in the form of cracks and shear bands. Common strategies to describe these localised deformation patterns mesh independently is to use nonlocal constitutive models [1] or to adjust the softening modulus of local constitutive models with respect to a length measure which is directly proportional to the element size. Nonlocal constitutive models are

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most commonly formulated as integral type nonlocal or gradient models in which the stress evaluation depends on spatial averaging of history variables [38] or spatial gradients of history variables [35], respectively. These models have shown to provide results for localised deformation patterns which are insensitive to mesh size and mesh orientation, if the mesh is chosen to be fine enough [46]. Nonlocal models are rarely used in commercial finite element programs, because they are difficult to calibrate and require very fine discretisations. Recently, a new calibration strategy for nonlocal models was proposed in [47], but more work is required to address the requirement for fine discretisation. On the other hand, crack band models based on an adjustment of the softening modulus [37,2] are commonly used in commercial finite element programs. These models can be used with a wide range of mesh sizes and can be relatively easily calibrated. For crack band models, global results in the form of load-displacement curves are in many cases insensitive to the mesh size. However, deformation patterns are often influenced by the mesh direction, since they localise in a mesh-size dependent zone [23]. Furthermore, in general 3D analyses, there is no straightforward approach how to define the length measure which is used to adjust the softening modulus of stress-strain curves [21].

In structural analyses of reinforced concrete, reinforcement is often modelled by beam or truss elements which are connected to solid elements. The constitutive model for the reinforcement is typically based on elasto-plasticity, where the plasticity part is either hardening or perfect plastic. Therefore, for the reinforcement itself, mesh-independent modelling is not difficult. For the interaction of reinforcement and concrete, either perfect bond or bond-slip laws are used [20]. For perfect bond, the nodes of the reinforcement are merged with those of the concrete elements, if the mesh is generated so that the location of nodes of reinforcement and concrete elements coincide. Alternatively, the degrees of freedom of the reinforcement are constrained within the concrete elements [36,12,20,6]. Perfect bond is often assumed in the failure analysis of structures with good bond conditions between reinforcement and concrete, such as for the case of deformed reinforcement bars, which contain ribs to increase the load transfer between steel and concrete [7]. For poor bond conditions or more complicated loading scenarios such as cyclic loading, bond-slip laws are used, which can be included by means of nonlinear springs [32,31,44] or interface elements [40,45] between coincident nodes of reinforcement and concrete elements. Alternatively, techniques to include bond-slip laws while constraining the reinforcement element within the concrete elements has been reported in [20,43]. An investigation of constrained approaches together with damage-plasticity models has been presented in [27]. If reinforcement elements are constrained in the concrete elements, the concrete can be meshed independently from the reinforcement, which simplifies the mesh generation for complex reinforcement arrangements and hexahedral elements. Therefore, the constrained techniques are commonly used in commercial finite element programs [10,11,16,20,42,43]. However, the numerical implementation of these constrained approaches for general conditions can be difficult.

Studies on the influence of mesh size on the response of reinforced concrete are much less frequent than for plain concrete structures. From the limited available results in the literature, it was shown that nonlocal models are able to reproduce the interaction of concrete and reinforcement mesh-independently for both perfect bond [45,34,46] and bond slip [45]. For crack band models, the influence of mesh dependence on crack patterns is less clear. It is generally accepted that the use of perfect bond together with crack band models produces mesh dependent crack patterns [45,46]. In [45], it was also shown that crack patterns obtained from dynamic 2D analyses with bond-slip appear to be mesh-dependent as well.

In the present study, the modelling of reinforced concrete with perfect bond and bond-slip was further investigated by means of 3D finite element analyses using merged and coincident with slip approaches. The reinforcement was modelled by means of beam elements. The merged approach was implemented using the same nodes for the reinforcement beams and concrete. The coincident with slip approach was introduced by means of springs between coincident nodes of reinforcement and concrete as proposed in [32,31,44]. It was aimed to show how mesh size influences the results of 3D analysis of an elementary benchmark reproducing the tension stiffening effect of reinforced concrete. The 3D mesh size study is one of the new aspects of this study. Furthermore, it was investigated which effect the assumption of perfect bond and bond-slip has on the structural performance of reinforced concrete structures by analysing tension stiffening experiments reported in [5] and dynamic drop weight impact tests reported in [28,26].

For concrete, the damage-plasticity constitutive model CDPM2 was used [15,14]. In this model, plasticity is formulated in the effective stress space and damage is driven by both elastic and plastic strains. This type of combination of damage and plasticity was originally proposed by [25] and has since then been used in many constitutive models for concrete [19,14,9,15]. The damage-plasticity model CDPM2 has shown to be able to reproduce important characteristics of concrete, such as strain softening and reduction of stiffness in tension and low-confined compression, as well as increase of strength and deformation capacity in confined compression. CDPM2 has been recently implemented as material model 273 in the general purpose finite element program LS-DYNA (Release 9.1.0) [17], which was used for the present analyses.

2. Method

The influence of the way how bond is modelled on the results of three-dimensional finite element analyses of the failure of reinforced concrete structures was studied by combining models for concrete, reinforcement and the interaction of reinforcement and concrete. In the following paragraphs, the models of the different components are discussed.

For concrete, the concrete damage-plasticity model 2 (CDPM2) proposed in [15] was used, which is an extension of CDPM proposed in [14]. For the details of the model, it is referred to [14,15]. In CDPM2, the stress evaluation is based on the damage