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Finite element analysis of dynamic concrete-to-rebar bond experiments in the push-in configuration

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ABSTRACT

Finite element analysis of concrete-to-rebar bond specimens under dynamic loading was conducted. This involved detailed modelling of the reinforcing steel bar ribs and the concrete keys in between. The modelling aimed to realise insight into the local structural phenomena and create a solid base for the prediction of bond behaviour under varying conditions. The analysis was performed in 3D with the explicit finite element code LS-Dyna. The proposed Soil and Foam Failure material model for concrete is described and definition of the material parameters is discussed. The numerical results are compared to experimental data obtained during dynamic push-in bond experiments carried out at the Technische Universität Dresden. Strain signals, slip measurements, bond stresses and crack patterns are analysed. The obtained signals are decomposed based on fundamentals of wave propagation. Significant influential factors like the experimental set-up geometry are hence identified. The capability of the model to predict key aspects of bond behaviour under dynamic loading is demonstrated and its applicability for future parametric studies is highlighted.

1. Introduction

Reinforced concrete is a composite material and the bond between its two components concrete and reinforcing steel provides its fundamental mode of action. Furthermore, the bond is one of the most critical aspects when it comes to the overall load bearing capacity of reinforced concrete structures. Thus, extensive research has been undertaken trying to investigate the behaviour of bond in the form of experiments, analytical models and finite element analyses. A large number of tests has been performed on both smooth and deformed bars, i.e. [1–3]. Several parameters like rebar diameter, rib geometry, concrete type, concrete cover and casting position on bond have been examined and were recognized as influential. A number of empirical equations describing bond behaviour based on test observations was proposed [4] and provided the basis of existing design codes like the CEB-FIP Model Code 2010 [5]. Empirical equations were also incorporated in supplementing numerical analyses, leading to a number of phenomenological finite element models [6–8].

Nevertheless, so far little attention has been paid to the investigation of bond behaviour under dynamic loading conditions. Shortcomings in the design of reinforced concrete structures against dynamic impact situations were demonstrated by a growing body of structural failures during recent terrorist attacks, aeroplane crashes and rock falls. Apart from some work undertaken for the needs of earthquake engineering [4], first experimental dynamic tests on bond behaviour were undertaken by Hansen and Liepins [9], Hjorth [10] and Vos [11]. Investigating the so-called strain rate effect is a continuing concern within this field. The term is used to describe the strain rate induced strength enhancement in materials, and concerns concrete and reinforcing steel as well as the bond between them. Debate still continues about the interpretation of the corresponding experimental findings and the best strategies of incorporating them into empirical equations and design codes. Further investigation and experimentation into dynamic loading processes is necessary.

The work described herein, is on modelling dynamic bond behaviour of experimental specimens using 3D analysis with the commercial finite element analysis software LS-Dyna. So far, the majority of finite element analyses incorporate macroscopic bond stress slip relations by implementing them into the software with use of contact algorithms or contact elements. In contrast to such phenomenological approaches, the present study involves detailed modelling of the rebar ribs and concrete keys cast between each pair of ribs. The advantages of this approach are twofold: It allows (1) insights into the local structural phenomena and (2) prediction of bond behaviour under varying conditions. In practice, parametric studies with such detailed models can extend the perception of bond behaviour to set-ups and influential factors other than the experimentally investigated ones. Phenomenological models on the other hand generally require more or less confirmed assumptions regarding the effect of specific parameters on the bond behaviour. The phenomenological

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approach thus leads to no other than the anticipated results, but has the advantage of a reduced computation effort.

As part of a research program at the Technische Universität Dresden, a drop tower was designed and constructed. A series of dynamic push-in bond experiments was conducted [12] and numerically analysed using the explicit finite element code LS-Dyna. The proposed Soil and Foam Failure material model (*MAT_014) is described and calibrated. The finite element results are presented and compared to the experimental ones. Fundamentals of wave propagation are used to decompose recorded strain signals and identify significant influential factors. Slip measurements, bond stresses and support reaction forces are analysed. Crack patterns are shown and discussed.

2. Experimental set-up

The proposed finite element model for the simulation of concrete-to-rebar bond was validated by a series of dynamic drop tower experiments. Basic characteristics of the experimental set-up are described in [12] and in Section 2.1.

2.1. Testing configuration and specimen geometry

Fig. 1 shows a schematic sketch of the drop tower, where the dynamic bond experiments were conducted. Cylindrical specimens with a diameter of 100 mm and a height of 100 mm were used throughout the program. They can be tested in two different drop tower configurations: push-in and pull-out. In the considered push-in configuration a drop weight (impactor) is utilized to introduce the load. The specimens are placed on a steel support plate below the impactor. Load cells are used to record the reaction forces. When the impactor hits the reinforcing steel bar, which protrudes out of the concrete body, a compressive pulse is transferred into the rebar which is pushed into the concrete. Relative displacement between the concrete and the rebar takes place. The bond mechanisms are activated and partial or complete bond failure follows. The extent of failure depends on the fracture energy of the bond and the amount of energy introduced. A given impactor mass and a maximal adjustable drop height (underlying technical restrictions) define an upper limit for the latter. In order to facilitate the analysis of proceeded bond degradation the length of the bond zone was chosen relatively short. In general, short bond zones allow a better investigation of localized bond behaviour and come the closest to the commonly made simplifying assumption of constant bond stresses over the bond zone length. The treated specimens bond zone had therefore a length of $l_b = 2\,d_s$, where d_s is the nominal diameter of the deformed reinforcing steel bar, amounting to 10 mm. It is located in the middle of the specimen with the rebar casted vertically inside the concrete. The entire length of the rebar is 500 mm. Plastic tubes are used to realise a bond free length in the vicinity of the support plate and to reduce lateral stresses. The tubes are removed prior to testing, such that the recorded results are not influenced by them. Friction is allowed to act between the concrete specimen and the support plate, since the friction induced lateral stresses are considered primarily concentrated at the lower specimen end and therefore uncritical at mid height of the cylinder, where the bond zone lies. The composition of the concrete specimens corresponds to the basic mechanical properties of normal weight concrete of strength class C35/45 according to Eurocode 2 [13]. A cylindrical impactor with a height of 500 mm and a diameter of 40 mm was chosen according to preliminary numerical studies in the course of test design. It is realized in steel and its overall mass resulted in 4.9 kg. The drop height was set to the maximal possible value and was set to $h_0 = 3.5$ m. Free fall hence speeds up the impactor to an impact velocity υ_0 of:

$$\upsilon_0 = \sqrt{2\,g\,h_0} = 8.287\,m/s \quad (1)$$

where g is the acceleration due to gravity. Loading rates in term of slip and bond stress rates are additionally evaluated in order to put the presented bond tests into perspective with available literature data. Accordingly, the here produced slip rate amounts to approx. 7 m/s, whereas the corresponding bond stress rate is approx. $2 \cdot 10^5$ MPa/s. The experiment is thus placed in the range of intermediate to high loading rate executions. Strain histories were recorded by strain gauges positioned on the rebar. They were located approximately 25 mm apart from the considered geometrical centre of the bond zone: one set was placed above and the other one below the bond zone. A detailed geometry of the specimen is given in Fig. 2b and c. Their differences regard the numerical modelling methodology only and will be discussed in Section 3.1.

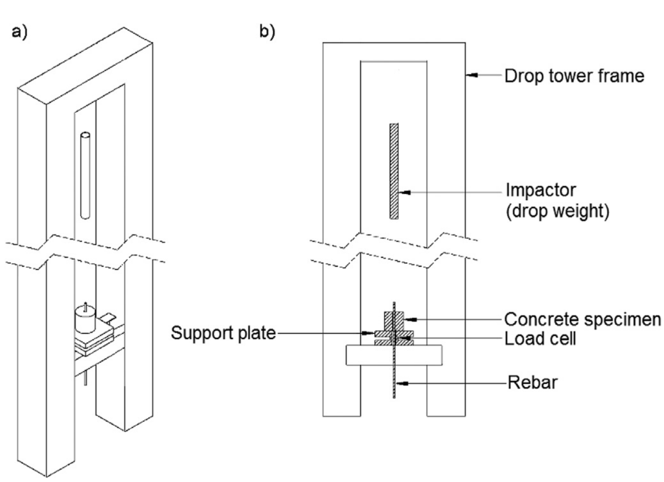

Fig. 1. Drop tower set-up: a) isometric view b) cross section, after [12].

2.2. Failure modes

Three fundamental failure modes of concrete-to-rebar bond can be identified in literature: rebar pull-out or push-in, splitting of the concrete cover and yielding of the steel. All examined specimens failed in the mode of rebar push-in, where the concrete keys between the ribs are sheared off and the rebar slips in a frictional mode of behaviour [14]. No splitting failure was observed.

Note that rebar pull-out and splitting of the concrete cover are the most commonly documented bond failure modes in reinforced concrete structures. A variety of test set-ups has been specifically designed for the purpose of experimental description of bond behaviour, whereby the beam test and the pull-out test are considered superior. First attempts to standardize them were made in the 1970s by RILEM [15,16]. In general, specimens with compact dimensions are however preferred over large format ones, since they permit simpler manufacture, handling and test execution. Pull-out tests are therefore widely established, while their corresponding results make up the bulk of available literature data. Push-in test are however especially under dynamic loading conditions easier to perform. They create a similar loading condition by applying a compressive force instead of a tensile one at the previously non-loaded rebar end. In case they are predominately used instead of pull-out tests, their comparability has to be ensured. The difference between them lies in the transverse rebar deformation due to the Poisson effect. A reduction of the cross sectional area of the rebar is the result for pull-out tests and the opposite applies for push-in tests. In regard of the results, the observed differences range between slightly higher