Numerical Study on the Pull-out Behavior of Steel Fibers in Cement-Based Composites

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Abstract

The interaction between steel fiber and surrounding cement-based matrix and concrete materials is crucial in the behavior of Steel Fiber-Reinforced Concrete (SFRC). This interaction is generally measured through a single fiber Pull-out test. Considerable research has been conducted in this field. However, efforts have been largely directed to the analytical and experimental methods, whereas very limited research has been performed using the finite element method. Having an authentic numerical model, numerical parametric studies together with experiments can serve as an essential tool to enhance the understating of bond behavior. Therefore, this study attempts to numerically investigate the behavior of fiber bonds in SFRC composites. The bond behavior was investigated using different approaches of modeling bonds in the LS-Dyna explicit software. The validation of the finite element model was performed with the comparison of computed and experimental pull-out force obtained from the literature. It is shown that the validation is possible for all investigated approaches and the computation results showed a strong agreement between pull-out force and relative displacement with experimental results of previous studies. Finally, the validated model is employed as a powerful tool to simulate the bond behavior of a single steel fiber embedded in a cement-based matrix.

Keywords: Pull-out; Bond behaviour; Fiber-reinforced composite; Steel fiber; Cement-based; Finite element

1 Introduction

In fiber-reinforced composites, the fiber and its surrounding matrix are rendered tight together through the so-called bond interaction. Understanding this interfacial behavior is essential for interpreting the global behavior of these materials. To investigate the bond behavior of the steel fiber and its adjacent cement base, numerous studies examined fiber pull-out tests using different testing configurations and different materials, for instance, see Friedrich & Wang (2016); Gray & Johnston (1984); Li et al. (1991); Morrison et al. (1988); Pinchin & Tabor (1978); Stang & Shah (1986). Though it is a big challenge to derive and extract the properties of steel fiber-reinforced composites from single fiber pull-out tests, the results obtained from these tests can provide an excellent idea of how to identify the mechanical properties of SFRC materials (Hughes & Fattuhi, 2012; Maage, 1977). Previous investigations performed by Naaman et al. (1992) and Banthia & Trottier (1995) reported that fiber to its adjacent matrix interfacial bond quality is always evaluated using the single fiber pull-out test configuration, in which fiber slip is addressed as a function in the fiber applied load خطأ! لم يتم العثور على مصدر المرجع. illustrates a typical pull load-slip behavior for straight, rounded and hooked-end steel fibers.

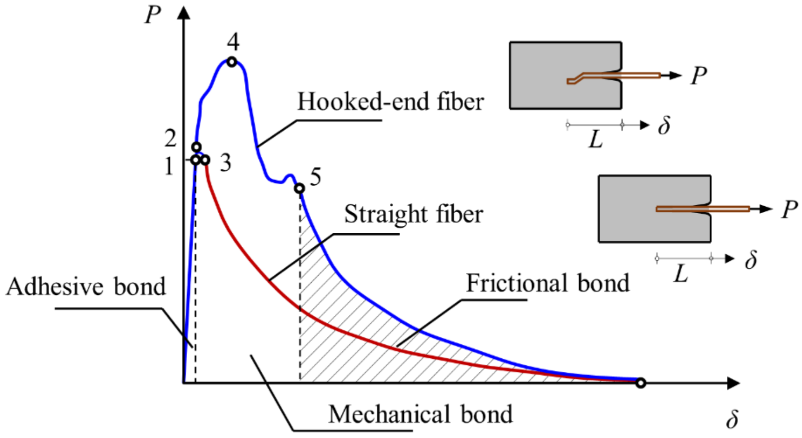


Fig. 1: Schematic representation of pull-out load-slip behavior, adapted from Kooiman (2000)

2 Methods of Modeling Bonds in Fiber-Reinforced Composite

Bond interaction between the reinforcing steel and surrounding matrix provides an essential process for SFRC composites. Embedding steel bars into the concrete matrix or cement-based materials should be implemented in such a manner that the cement-based matrix resists the compressive stresses acting in the structural elements. In contrast, steel reinforcement resists tensile stresses. Bond action of the matrix and embedded steel bars is generally acquired by three different mechanisms: chemical adhesion, mechanical friction, and mechanical interlocking. The function of each depends highly on the composition of the particular structural member. Many techniques are nowadays available in LS-Dyna commercial finite element software to model bond, de-bond, and sliding mechanisms between the reinforcing bar and the surrounding matrix, for instance, shared nodes, constraint nodes, and one-dimensional contact algorithms. If needed, the constraint method can be operated with a pre-defined bond-slip relationship. These methods are described in the following:

2.1 Merged Common Nodes

The merged common nodes are widely known as shared nodes. In this technique, the so-called perfect bond between the continuum Lagrangian and the embedded beam or truss elements can be realized by merging the common nodes of the two parts. This process enables the nodes of the continuum Lagrangian to share the same locations as those of the beam or truss elements (LSTC, 2018; Schwer, 2014). خطأ! لم يتم العثور على مصدر المرجع. shows a representation of the concept of shared nodes.

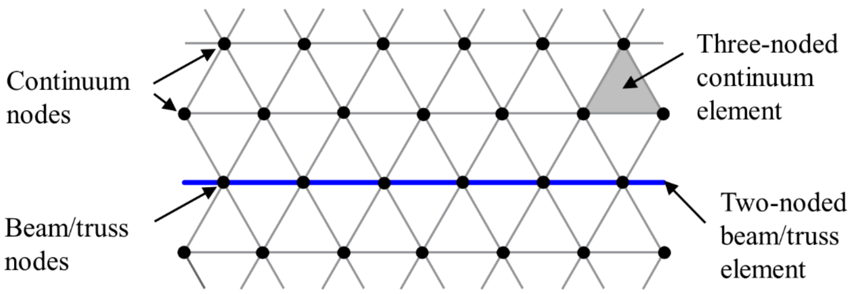


Fig. 2: Concept of the shared or merged nodes

2.2 Constraint Methods

Unlike the previous method, here in a method, the keyword *CONSTRAINED_BEAM IN_SOLID (CBIS) can be utilized to achieve the perfect bond by embedding the beam or truss elements into the Lagrangian elements with full kinematic compatibility. The CBIS option was developed and implemented in LS-Dyna code to avoid certain limitations of the previous keyword *CONSTRAINED LAGRANGE_IN_SOLID keyword (CLIS). In this option, the beam or truss elements are constrained to move over with the Lagrangian continuum. In the CBIS, no coincidence nodes of solid elements and beam elements are required, therefore; each part can be discretized independently, and the movement of the two discretizations is constrained automatically (Bermejo et al, 2014; LSTC, 2018; L. Schwer, 2014). A schematic representation of the constraint nodes method is presented in خطأ! لم يتم العثور على مصدر المرجع..

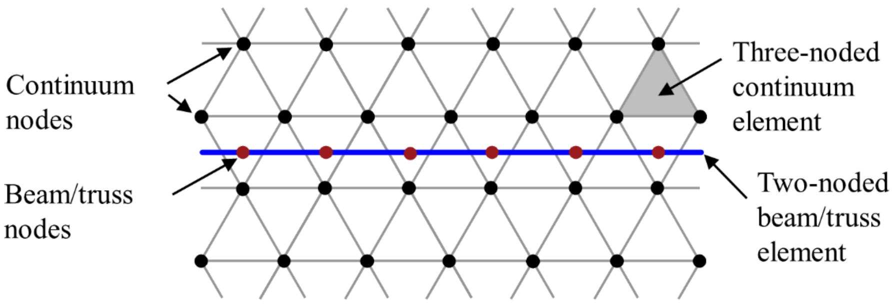


Fig. 3: Concept of the constraint nodes

2.3 One Dimensional Contact Algorithmic

The bond behavior of the reinforcing steel and the surrounding concrete and cement-based matrix can also be modeled using the so-called 1D (one-dimensional) contact law implemented in LS-Dyna explicit finite element software. This contact algorithm can be defined using LS-Dyna keyword *CONTACT_1D using the following expression.

$$u_{max} = SMAX\ e^{-EXP \cdot D} \tag{1}$$

where D defines the damage parameter, which is the sum of the absolute values of the plastic displacement increments $D_{n+1} = D_n + \Delta_u$, u_{max} represents the maximum permissible slip-strain, EXP is the damage curve exponent, and $SMAX$ the maximum shear strain.

By taking into consideration accumulative damage, the interfacial bond between the reinforcing bar and the surrounding concrete matrix is decomposed in a two-phase model. In the elastic range, the bond strength is linearly proportional to the relative slip S. After reaching the maximum bond strength τ_{msx}, the bond shear will decay exponentially in the plastic zone.

$$\tau = \begin{cases} GBS, & S \leq SMAX \\ \tau_{max} e^{(-EXP \cdot D)}, & S > SMAX \end{cases} \tag{2}$$

3 Experimental Setup

In FRC structural members, bond failure is most often achieved due to fiber Pull-out and splitting. خطأ! لم يتم العثور على مصدر المرجع. presents a test setup of the single fiber Pull-out test set-up. It is a servo hydraulic apparatus. An experimental investigation of Shannag et al. (1997) will be adopted in this work to validate the reliability, convergence, and accuracy of the finite element models and their chosen contact algorithms. For more details, see (Shannag, 1997).

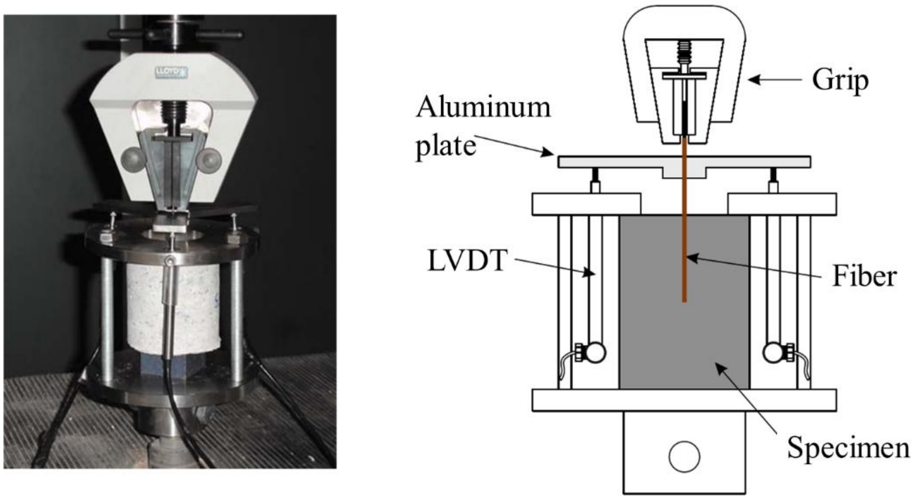


Fig. 4: Single fiber pull-out test setup, according to Shannag et al. (1997)

4 Finite Element Simulations

In this research, three different finite element models were developed to investigate the behavior of the single fiber pull-out test in a cement-based composite. Each model has a different contact algorithm that defines the interfacial contact between the cement-based matrix and steel fiber. Their properties and modeling aspects are presented in the following section:

4.1 Geometry and Discretization

A three-dimensional numerical model of the single fiber pull-out test was developed, including the cylindrical cement-based matrix and the embedded straight and rounded steel fiber. The bonded segment of the fiber is set to 12 mm, which is located in the middle of the cement-based cylindrical specimen and has a diameter of 16 mm and a length of 32 mm, see خطأ! لم يتم العثور على مصدر المرجع..

Each numerical model has 1,248 eight-noded hexahedron Lagrangian elements for the cement-based matrix and 5 two-noded beam elements for the fiber. To keep the model simple and minimize the computational time, the Hughes-Liu formulation was adopted for the steel fiber, whereas one point integrated solid formulation was used in the simulation for the cement-based matrix. The mesh size chosen for both parts, cement-based matrix and steel fiber, was 4 mm. The overall number of the elements and nodes used for any part in each model is listed in **Table 1**. The static displacement loadings were applied at the top endpoint of the steel fiber using LS-Dyna keyword *PRESCRIBED_MOTION_NODE, see خطأ! لم يتم العثور على مصدر المرجع.. The cylindrical specimen was constrained against any movement in the x, y, and z directions at the top surface nodes. In this study, the time-step scale factor is set to a default value of 0.9, which is the most significant value to ensure minimum computational time and result accuracy.

Table 1: Elements and nodes in each simulation

Phase	Number of elements	Number of nodes
Matrix	1,248	1,521
Steel fiber	5	6

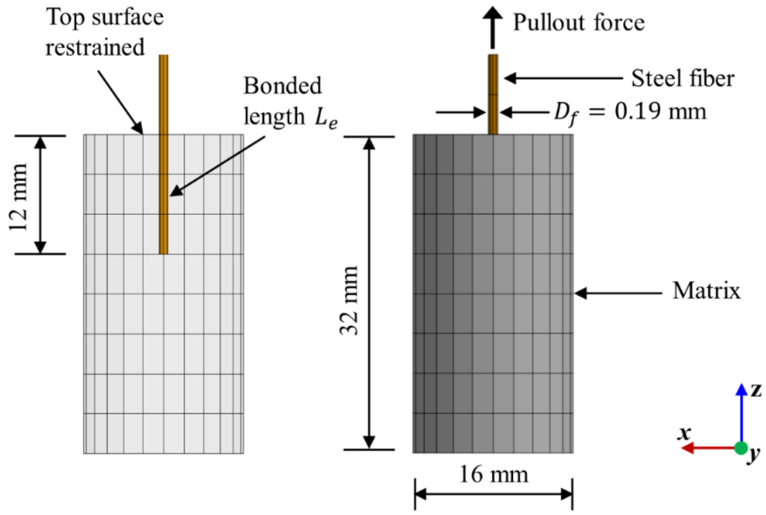


Fig. 5: Finite element discretization of single fiber Pull-out test

4.2 Conistitutive Material Model

For any phase of the finite element model, an adequate material formulation needs to be defined. In this work, the mechanical material parameters of Shannag et al. (1997) were adopted. This allows the verification of the simulated results with the experimental ones. Within previous studies, a large number of constitutive material formulations in the LS-Dyna finite element were investigated and analyzed by many researchers to their capabilities of modeling such types of bond problems (Babiker et al., 2022; Fang & Zhang, 2013).

LS-Dyna finite element code provides a large number of material models that can be applied for concrete and cement-based materials, including the Continous Surface Cap Model (*MAT_159), Schwer and Murray Cap Model (*MAT_145), Winfrith Concrete (*MAT_084), Karagozian and Case (*MAT_072R3) and many others. In this work, Schwer & Murray Cap Model (SMCM) was adopted due to its better capabilities of simulating such problems. The SMCM is a three-invariant extension of the Geological Cap formulation. This material involves visco-plasticity to account for the strain-rate effect and also utilizes damage mechanics to include strain softening and modulus degradation in both tension and compression. More details about this formulation and parameters adjacent can be found in (Schwer (1994; Schwer & Murray, 2002).

The steel fiber is assumed to behave as elastic ideal plastic without hardening. The material model Piecewise Linear Plasticity (*MAT_024) was employed to define the material parameters of the steel fiber. The rate effect is irrelevant in the research, therefore; it was ignored. **Table 2** gives the material parameters defined in each model according to the experimental data.

Table 2: Material parameters

Parameter	**Matrix**	**Fiber**
Unit weight [kg/m^3]	2400	7850
Compressive strength [G[1]Pa]	0.040	-
Tensile strength [GPa]	0.0035	2.99
Modulus of elasticity [GPa]	25	200
Poisson’s ratio [-]	0.2	0.3

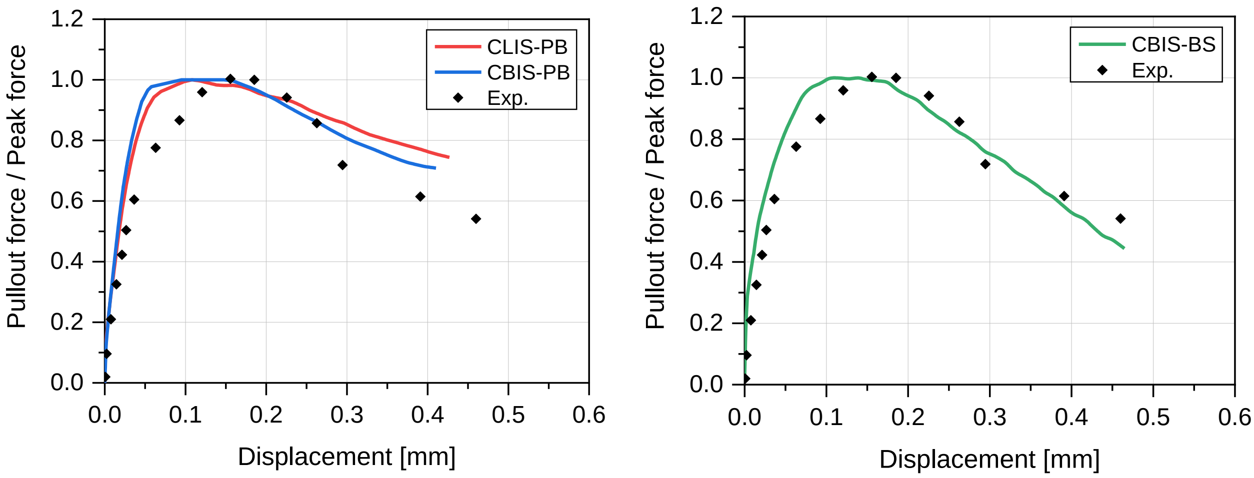
[1] GigaPascal

4.3 Contact Algorithm

As discussed in Section 2, numerous methods are available in the LS-Dyna finite element to simulate the interfacial behavior of the steel fiber and the cement-based matrix. In this research, three different methods were investigated. In the first step, the perfect bond was achieved with constrained nodes using *CONSTRAINED_BEAM_IN_SOLID. In the second step, the perfect bond was modeled with constrained nodes using *CONSTRAINED_LAGRANGE_IN_SOLID. Finally, the constrained method was used again, but this time with a pre-defined bond-slip curve. This method was utilized using the *DEFINE_FUNCTION keyword. The pre-defined bond-slip curve was written in Fortran syntax and then implemented into the LS-Dyna finite element code. The three investigated methods will be identified later as CBIS-PB, CLIS-PB, and CBIS-BS, respectively.

5 Finite Element Results

The computed pull-out force versus relative displacement curves are illustrated in **Fig. 6**, along with the experimental data.



(**a**) perfect bond (**b**) bond-slip

Fig. 6: Pull-out-displacement curve in comparison to the simulation results

According to **Fig. 6**(a), it can be observed that there is a good correspondence between the predictions of the simulated perfect bond methods and the experimental results. Accordingly, both the constraint nodes and shared nodes methods in LS-Dyna are considered to be acceptable approaches for handling the perfect bond between the embedded fiber and the adjacent cement-based matrix. The pull-out versus displacement relationship computed using a pre-defined bond slip, seen in **Fig. 6**(b), also largely corresponds to experimental results, especially when it comes to the strain-softening behavior.

Based on the obtained result of this work, it can be concluded that the CBIS and CLIS techniques of LS-Dyna finite element code can well capture the bond interaction between the cement-based matrix and the embedded steel fiber; therefore, they are recommended for modeling such problems and also can be used in comprehensive parametric studies on different aspects such as fiber diameter, fiber embedded length, fiber shape, material formulation, bond law, loading rate, and many others.

Furthermore, **Fig. 7** gives the propagation of the effective plastic strain on the cement-based matrix during the analysis. It should be mentioned that the damage patterns in **Fig. 7** are the result of the PB-CBIS method.

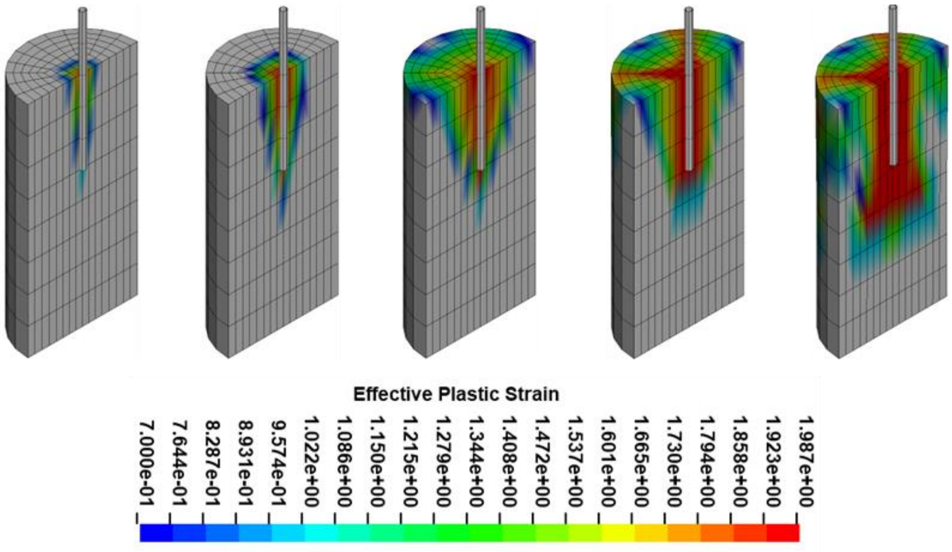


Fig. 7: Damage states at the center cut plane for the CBIS-PB configuration

6 Conclusions

The presented paper gave a brief description of finite element investigation on the pull-out behavior of steel fiber in a cement-based composite. Three different methods of bond modeling in LS-Dyna finite element commercial software were examined. The developed finite element models were validated against the experimental result with good agreement. Based on the simulated results of this work, the following conclusions may be derived.

It is demonstrated that the merged and constrained nodes methods of LS-Dyna finite element code can well capture the pull-out behavior of steel fiber in a cement-based matrix. A future study has to investigate the capabilities of the 1D (one dimensional) algorithm of LS-Dyna, and the influence of mesh density and many other influential parameters to derive further benefit from these models and also to identify any exciting limitations they may have.

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