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Numerical modelling of the concrete/rebar bond

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Abstract

The simulation of the behaviour of the rebar-concrete bond is of primary importance for an accurate description of cracking processes in reinforced concrete structures and an improved prediction of their durability. In this paper, the methodology used to identify the mechanical behaviour of a rebar-concrete bond in the case of a particular steel reinforcement is first mentioned. The methodology consists in simulating the probabilistic mechanical behaviour of RC tie-beams (170 x 10 x 10 cm), subjected to tension, using a probabilistic approach for the mechanical behaviour of the concrete and a deterministic model for the concrete/rebar bond. The tie-beams are reinforced by a flat steel rebar with a rectangular cross section (25 x 3.5 mm).

This approach at macro-scale level is compared to another one at micro-scale level in which notches/indentations of the flat steel rebar are explicitly taken into account in the simulation, the bond behaviour being considered through the local concrete cracking around the rebar.

The following conclusions can be made from this study:

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- The modelling of the concrete/rebar bond by an interface element having damage behaviour is relevant if the modelling of concrete cracking is physically and quantitatively relevant.
- The concrete/rebar bond behaviour can mainly be considered as the consequence of concrete micro-cracking around the ribbed rebar (it means due to the presence of notches/indentations).
- This micro-cracking concerns a zone with a thickness similar to the rebar one.

Keywords:

Reinforced Concrete, Flat Steel, Concrete/Rebar Interface, Cracking

1. Introduction

In the process of developing a new technological solution of reinforcement for RC structures, it is of great importance to understand and identify the main physical mechanisms involved. Numerical simulation tools can then be very useful to demonstrate, for example, the mechanical relevancy of the solution. A French construction company has developed in recent years, a new type of flat steel reinforcement with notches/indentations (Figure 1). It can be used in structural elements and shows some advantages:

- reduction of the total thickness of the structure by reducing the thickness of the steel,
- decrease in the quantity of steel by using tendrils replacing the anchorages of steel round rebars,
- increase in relative surface of adhesion,
- easy implementation.

Mechanically speaking, the main difference between this new type of steel reinforcement and the traditional one (cylindrical rebar) concerns the interface behaviour between the flat steel and the concrete. So, the modelling of the interface behaviour is very important for a relevant analysis of the behaviour of the structure reinforced with this type of steel reinforcement.

In this work, it has been chosen, as a starting point, to model a tie-beam reinforced by flat steel and subjected to axial tension. The study is mainly focused on the mechanical effect of the concrete/rebar bond on the cracking process of the tie-beams. The behaviour of the concrete in tension is represented by a probabilistic cracking model [1, 2], which takes into

account the heterogeneity of the material and its inherent scale effect and gives an explicit representation of the cracks in the concrete.

Concerning the concrete/rebar bond, three strategies of modelling are considered:

1. In the first one, called macro-scale level strategy, the concrete/rebar bond is represented by standard interface elements. Their behaviour is described by a simple deterministic damage model which macroscopically takes into account the main physical phenomena of the interface through only two parameters: cohesion and slip (i.e. tangential relative displacement between steel and concrete).

An inverse analysis approach is used to identify the parameters of this type of behaviour. The numerical results are compared with those of the experimental ones [3]. The comparison is made in terms of global response (load vs. relative displacement), as well as local information (cracks opening, cracks spacing and number of cracks).

2. In the second one, called mix-scale strategy level, two manners of representing the concrete/rebar bond are considered in the same numerical simulation:
 - In the central part of the steel rebar, on a length of 30 cm, the notches/indentations of the flat steel rebar are explicitly taken into account in the simulation and no interface elements are used.
 - In the rest of the rebar, the interface is modelled as previously by interface elements.

Concerning the part of the rebar where the notches/indentations are explicitly modelled, the concrete/rebar interface behaviour is taken into account only by the concrete cracking around the rebar (the bond between the rebar and the concrete being

- considered as perfect) while, in the rest of the rebar, the values of the parameters related to the interface elements are the same than those previously determined.
3. In the last one, called micro-scale level strategy, the notches/indentations are explicitly modelled along the totality of the rebar (without any interface elements and with a perfect bond between the concrete and the rebar).

The purpose of this paper and of the use of the proposed multi-scale strategy of modelling is to evaluate if:

- the cracking behaviour of reinforced concrete is correctly modelled by using a very simple macroscopic model of the concrete/rebar bond if the modelling of concrete cracking is correctly done (physically based) ?
- it is possible, in a same numerical analysis, to get, at the same time, global information related to macro-cracks around the rebar and very local one related to micro-cracks situated in very small zone around this ribbed rebar ?
- the concrete/steel bond behaviour is mainly due to the micro-cracking of the concrete around the ribbed rebar (due to the presence of notches/indentations) ?

2. Presentation of the concrete cracking model

The behaviour of concrete is represented by a probabilistic cracking model developed at the IFSTTAR² (formerly LCPC³) by Rossi [1] and recently improved by Tailhan et al. [4]. This model has the particularity to take into account two major characteristics of concrete: heterogeneity on the one hand and its sensitivity to scale effects, on the other hand [2]. The physical basis of the model (presented in detail in the past [1, 2]) can be summarized as following:

- The heterogeneity of the concrete is due to its composition. The local mechanical characteristics (Young's modulus E_b , tensile strength f_t) are randomly distributed.
- Scale effects are also a consequence of the heterogeneity of the material. The mechanical response of the material directly depends on the volume of material stressed.
- The cracking process is controlled by the presence of defects in the cement paste, by the heterogeneity of the material and by the development of tensile stress gradients.

In terms of numerical modelling (in the frame of finite elements method), these physical evidences can be taken into account as following:

² IFSTTAR - The French institute of science and technology for transport, development and networks
³ LCPC - French Public Works Laboratory

- The tensile strength is initially randomly distributed on all elements of the mesh using a probability distribution whose characteristics depend on the *volume of the finite element/volume of the largest aggregate* ratio. So, for a given concrete, the distribution functions related to a given mesh are known [1, 4].
- A crack is represented by the fact that the stiffness of a volume element becomes equal to zero. That happens when the principal tensile stress at the centre of the element reaches the tensile strength (which is randomly distributed in the mesh) attributed to this element.
- The cracking propagation in concrete is, in this model, the result of the creation of elementary “holes” that appear randomly.

The distribution function of the concrete tensile strength used in the numerical calculation is determined by just knowing the *volume of the finite element/volume the largest aggregate* ratio and the concrete average compressive strength [1, 4].

3. Presentation of the concrete/rebar bond modelling

Many studies have been performed to simulate the behaviour of RC structures taking into account the behaviour of the concrete/rebar bond (models based on the plasticity theory [5] or the damage theory [6, 7]). But very few of them were focused on the role of this interface in the cracking process of the concrete.

In this section, a simple and robust interface model is presented. It takes into account the nonlinear behaviour of the concrete/rebar bond in the frame of damage mechanics. It can also takes into account physical phenomena of concrete/rebar bond such as interface sliding, cracks appearance and degradation process. The interface zone is represented by interface elements that connect the concrete to the rebar. Their role is:

- to ensure the displacement continuity between the concrete and the steel before the slip of the interface and before the concrete cracking and consequently to ensure the transfer of load (and therefore of stresses) between steel and concrete.
- to represent the macroscopic mechanical effect of the rebar at the ribs level (which are not explicitly represented in the mesh).
- to simulate a local failure between steel and concrete along the rebar, if a shear cracking occurs and leads to a loss of the local adhesion.
- to simulate the local friction between the concrete and the steel after the interface failure.

The model is implemented in 2D and 3D. It considers the concrete/rebar bond as a material zone that progressively degrades in shear (the tensile failure is neglected). During this degradation, and before the total failure of the interface, stresses are considered to be still transmitted to the concrete.

A very simple approach is chosen, based on a damage model which maintains a constant level of stress when the critical shear has been reached (figure 2). When the relative tangential displacement between the concrete and the rebar exceeds a critical value, the interface element is declared broken [8]. After the failure, friction behaviour of Mohr-Coulomb's type is considered.

The interface model is considered as deterministic. The use of a deterministic approach for the interface behaviour is justified by the fact that cracking process around the rebar is not governed by the concrete heterogeneity but by the presence of the ribs along the rebar [8].

In 3D, the constitutive relations of the model can be summarized by:

$$\begin{bmatrix} c_n \\ \tau_1 \\ \tau_2 \end{bmatrix} = (1 - d) \begin{bmatrix} k_n & 0 & 0 \\ 0 & k_{t1} & 0 \\ 0 & 0 & k_{t2} \end{bmatrix} \times \begin{bmatrix} \delta_n \\ \delta_{t1} \\ \delta_{t2} \end{bmatrix} \quad (1)$$

Where, σ_n , τ_1 , τ_2 are the normal and tangential stresses in two directions, d is the damage parameter, δ_n , δ_{t1} and δ_{t2} are respectively the normal and tangential displacements and k_n , k_{t1} , k_{t2} the normal and tangential stiffness of the contact element. The values of k_n , k_{t1} , k_{t2} can be found in the recommendation of some commercial finite element codes (as, for example, CESAR [9] or CODE ASTER [10]).

The damage evolution (Figure 3(b)) is given by:

$$\begin{cases} d = 0 & |\delta_t| < \delta_t^e \\ d = 1 - \frac{\delta_t^e}{|\delta_t|} & \delta_t^e < |\delta_t| < \delta_t^{crit} \\ d = 1 & |\delta_t| > \delta_t^{crit} \end{cases} \quad \text{if} \quad (2)$$

Where, $\delta_t^e = f(C, k_{t1}, k_{t2})$ is the threshold of tangential elastic displacement (C being the cohesion parameter), δ_t^{crit} is the critical tangential displacement ($\delta_t^{crit} \geq \delta_t^e$), and $|\delta_t| = f(\tau, k_{t1}, k_{t2})$ is the parameter which drives the evolution of damage. In order to ensure the positiveness of the thermodynamic dissipation, the damage can only increase. As a consequence, this can be summarized as:

$$\begin{cases} \dot{d} \geq 0 \\ d = \max(d_0, d) \end{cases} \quad (3)$$

Where d_0 is an initial damage state and d is the actual damage state.

After the failure, when $\delta_t > \delta_t^{cri}$ and $d = 1$, a friction behaviour is considered and a Mohr-Coulomb type criterion is applied (Figure 3). In that case, an associated flow rule g is also used:

$$\left\{ \begin{array}{l} g = |\tau| - \sigma \tan \psi \\ \tan \varphi = \tan \psi \end{array} \right. \quad (4)$$

Where $\tau = f(\tau_1, \tau_2)$ is the resultant tangential stress, ψ the dilatancy angle and φ the friction angle. Without any further information concerning φ and ψ and considering that the failure essentially occurs in the concrete surrounding the steel, a value of 30° is retained (value obtained from Rossi [8]).

In this study, only the values of the maximum shear stress, C , and of the tangential critical relative displacement, δ_t^{cri} , have to be determined. This identification is made by a numerical inverse analysis based on a comparison with experimental results. In consequence, this determination is available only for a given rebar geometry and a given concrete.

4. Modelling of the tie-beam test - Use of a flat steel rebar

An example of the ribs of the flat steel rebar studied in the frame of tie-beam tests is presented in figure 1.

4.1. Presentation of the tie-beam test

The experimental tests on tie-beams were conducted in the laboratory of Polytech Clermont-Ferrand (Blaise Pascal University of Clermont-Ferrand, France). In these tests, the reinforced concrete tie-beams was subjected to pure tension. The dimensions of the concrete prismatic specimens were: $170 \times 10 \times 10$ cm. The reinforcement was a flat steel with a rectangular cross section of 25×3.5 mm. The steel rebar was centred in the middle of the tie-beam. To minimize edge effects in the concrete during the test, “no friction zones” of 10 cm length were considered at each extremity (figure 4).

Figure 4 schematizes the experimental device and figure 5 shows a general view.

To measure the elongations of the concrete and the steel, six displacement sensors (LVDTs) were placed on the specimen (Figure 4). These LVDTs were fixed on a common undeformable support independent of the specimen.

Two sensors (LVDTs 5 and 6) were located on the steel rebar (on both extremities of the tie-beam).

Four other sensors (LVDTs 1, 2, 3 and 4) on each face of concrete at the top and bottom of the tie-beam were also placed.

As a consequence, each couple of LVDTs provided the measurement of a relative displacement on the base length of 170 cm or 150 cm respectively. The six displacement sensors and the two load sensors were connected to a central acquisition system where the information was automatically recorded.

The tests were run with a load rate corresponding to a quasi-static condition so without any influence on results. During this loading procedure, steps were realized to measure crack opening evolution at the surface of the specimens.

During this experimental study, 9 specimens were tested.

4.2. Concrete and steel reinforcement

The concrete used in these tests is a C40/50 one, and its mix design formula is reported in table 1.

To determine the material characteristics of the concrete, compressive tests were performed on standardized cylindrical specimens (160 mm in diameter and 320 mm high). It must be noticed that the compressive tests were performed at the same age as the tie-beam tests, and under the same conditions of preservation.

Table 2 gives the material characteristics of the concrete and the flat steel rebar, considered in the numerical simulations.

4.3 Strategy of analysis of the test

A strategy of analysis of the tests results is proposed to get a consistent method to analyse the experimental tests and the calculations.

Determination of the mean crack opening

- At each loading step, the cracks opening is measured on each side of the specimen by using a fissurometer.
- A crack is counted if it is seen across an entire width of one side of the specimen, i.e. two adjacent edges are open. The opening of this crack is equal to the average of the openings related to the adjacent edges. For example, in figure 6, Face 1 presents two opened adjacent edges ($w_1 \geq 0$ and $w_2 \geq 0$); a crack is then counted, having a width given by:

$$w = \frac{w_1 + w_2}{2} \quad (5)$$

and Face 2 presents only one opened ($w_2 \geq 0$); then no crack is counted on this face. For this kind of test, and according to Eurocode 2 [11] in the case of RC structures, a crack is

considered only if its opening w is equal to or higher than $300\ \mu\text{m}$ (value which corresponds to prejudicial crack opening for service limit states).

- For each face, the average of all cracks openings (if cracks are counted on this face) is computed.
- The final mean value of the cracks opening of the tie-beam is given by the average of the preceding mean values (if it exists) obtained for each face.

Determination of the number of cracks and cracks spacing

The same strategy is adopted.

Note that this results analysis strategy can be performed on the 3D experimental test configuration as well as on the ones of the 2D and 3D modelling. Although this strategy only considers cracks of openings $\geq 300\ \mu\text{m}$, the model is able to describe smaller crack openings. These smaller cracks are not taken into account in this analysis.

4.4 Parametric study-Determination of the parameters values of the interface model

In the following work, only 2D numerical simulations are considered (plane stresses conditions).

This work consists, in a first step, to identify the parameters of the behaviour of the concrete/rebar bond by an inverse analysis approach. The numerical results are compared with the experimental ones.

The mesh adopted for the 2D numerical simulations is given in figure 7.

Linear triangular elements are used for both concrete and steel reinforcement, whereas linear interface elements are used to represent the steel/concrete bond. The probabilistic cracking model and the interface model, described above, are applied on concrete and steel/concrete

bond respectively. The steel behaviour remains elastic as far as only the service limit state is considered.

The damage model parameters (the cohesion C and the critical tangential relative displacement δ_t^{cri}) describing the behaviour of the steel/concrete bond have to be determined (it is the objective of the inverse approach).

The parametric study is realized by considering different cohesion C (6 MPa, 10 MPa, 15 MPa, 20 MPa, 25 MPa, 30 MPa) and critical tangential relative displacement δ_t^{cri} (6 μm , 10 μm , 15 μm , 20 μm , 25 μm , 30 μm) values of the concrete/rebar bond behaviour in total of 36 configurations. In order to compare numerical simulations to experiment, 9 calculations per configuration have been performed by Monte-Carlo method (each simulation corresponding to one random distribution of mechanical properties in the concrete). A total of 324 calculations have been performed for this parametric study.

The objective of these calculations is to determine the (C, δ_t^{cri}) couple of values which leads to the better fitting of the experimental results. So, the inverse approach proposed is a simple fitting one.

The material characteristics used in the numerical simulation are presented in table 2 (except for C and $\delta_{t,cri}$, all the others material parameters are experimentally determined).

4.5 Numerical results and comparison with experiments – Macro-scale level

The numerical results of the parametric study have been analyzed in the same way than those related to the experiments and as detailed in chapter 4.3. The comparison has been made at a global level (load vs. displacement curves) and also at a local level (analysis of the cracking: number of cracks, cracks openings and cracks spacing vs. load). It is recalled that only cracks widths openings greater than or equal to 300 μm are considered.

Figure 8 presents an example of the 2D numerical cracking profile of the tie-beam, showing, explicitly, the cracks pattern (for a loading level of 40 kN).

The analysis of the numerical results follows the strategy developed in chapter 4.3 (the same procedure was used for the experimental results). The comparison of these numerical results with the experimental results leads to the following conclusion: the couple of parameters, $C = 10 \text{ MPa}$ and $\delta_t^{\text{cri}} = 10 \text{ }\mu\text{m}$, gives the best results.

Figure 9 summarizes this comparison in terms of mean curves.

It appears that the numerical approach is efficient to represent the global response as well as local information (about cracks) of the behaviour of the tie-beam in tension (this despite the rough assumption of a 2D simulation of a 3D experiment).

4.6 Numerical results and comparison with experiments – Mix-scale level

As presented in the introduction, the concrete/rebar bond can be represented following two manners in the same numerical simulation: in the central part of the steel rebar, on a length of 30 cm, the notches/indentations of the flat steel rebar are explicitly taken into account in the simulation while in the rest of the rebar, the interface is modelled as previously by interface elements.

In the part of the rebar where the notches/indentations are explicitly modelled, the concrete/rebar interface behaviour is taken into account only by the concrete cracking around the rebar (probabilistic cracking model presented in chapter 2).

It is important to precise that the parameters values of the interface behaviour are those determined in the chapter 4.5 ($C = 10 \text{ MPa}$ and $\delta_t^{\text{cri}} = 10 \text{ }\mu\text{m}$).

In figure 10 is presented the mesh used for this “double scale approach” simulation (2D simulation) and an example of cracking profile obtained with the numerical simulations.

Note that, in this mesh, both parts (refined and not refined) are interlinked via the mesh nodes, ensuring therefore the continuity of the displacements. In addition, since the probabilistic cracking model takes into account volume effects, the strength of each concrete element directly depends on its own volume, it avoids therefore any mesh sensitivity of the results.

Figure 11 summarizes the results obtained in terms of mean curves.

These figures 10 and 11 allows the following comments:

- The cracking process (especially if cracks with openings greater than or equal to 300 μm are considered) obtained by combining, in the same simulation, two scales of modelling (macro-scale with interface elements and micro-scale by explicitly taking into account the rebar ribs) is similar to the one obtained by testing (Figure 11).

This positive result indicates that this two scales approach (in a same simulation) is fair and that the concrete/rebar bond behaviour can mainly be considered as the consequence of concrete micro-cracking around the ribbed rebar.

- In the part of the rebar where the notches/indentations of the flat steel rebar are explicitly taken into account, it is found that the micro-cracking zone surrounding the rebar has a thickness similar to the rebar one (Figure 10).

4.7 Numerical results and comparison with experiments – Micro-scale level

At this level, the notches/indentations are explicitly modelled along the entire rebar.

Therefore, the mesh is made by taking the same pattern than the one in the central part of figure 10, but repeating it other the entire length of the tie beam. As already detailed in the preceding section, the probabilistic concrete cracking behavior is used here for describing all

cracking processes around the steel rebar: deterioration of the steel/concrete bond and also cracking in concrete.

As for the other levels of simulation (chapter 4.5 and 4.6), an example of cracking profile is presented in the figure 12. The results in terms of mean curves are summarized in figure 13.

These figures 12 and 13 allow the following comments:

- Concerning the thickness of the micro-cracked zone surrounding the rebar, the simulation at the micro-scale level gives similar information than at the mix-scale level: this thickness is around the same that the rebar thickness (Figure 12).
- The results (in term of cracks opening and spacing) obtained at this micro-scale level (Figure 13) are very acceptable if it is considered that the 2D modelling of the notches/indentations along the flat rebar is very simplistic compared with the reality.

5. Conclusions

This work is related to the numerical modelling (finite elements method) of the concrete/rebar interface. Three strategies of modelling have been considered to model this interface:

- A Macro-scale level: the concrete/rebar bond (the rebar is a flat steel one with notches/indentations) is represented by standard interface elements.

- A Mix-scale level: the notches/indentations of the rebar are explicitly taken into account in the central part of the rebar while the interface is modelled by interface elements in the rest of the rebar.
- A Micro-scale level: the notches/indentations are explicitly modelled along the entire rebar.

A macroscopic discrete probabilistic cracking model is chosen to describe the concrete cracking process around the rebar.

At the macro-scale level, the values of the parameters of the interface element behaviour (the maximum shear stress, C , and the tangential critical relative displacement, δ_t^{cri}) are determined through an inverse analysis approach. This one consists in a parametric analysis which permits to determine the values of these parameters fitting well experimental results. These experimental results are obtained in the frame of tie-beams reinforced by a flat steel rebar (with ribs) and subjected to tension.

This first part of the work and of the paper shows a good agreement between experience and modelling both when the global behaviour of the tie-beam and its cracking process (crack openings, number of cracks and cracks' spacing) are concerned. It means that the use of an interface element (having a deterministic macroscopic behaviour) with a discrete probabilistic cracking model is physically and quantitatively relevant to model the cracking behaviour of reinforced concrete.

The mix-scale and micro-scale levels numerical simulations lead to the following conclusions:

- To model the concrete/rebar bond (without notches/indentations) by an interface element having damage behaviour is equivalent to model micro-cracking of concrete

around the rebar (with notches/indentations) if the objective is to get information about macro-cracks around this rebar.

The concrete/rebar bond behaviour can mainly be considered as the consequence of concrete micro-cracking around the ribbed rebar (it means due to the presence of notches/indentations).

- This micro-cracking concerns a zone with a thickness similar to the rebar one.

It is important to underline that all the results (values of the interface behaviour parameters) and conclusions are valid and relevant for the types of concrete and rebar studied.

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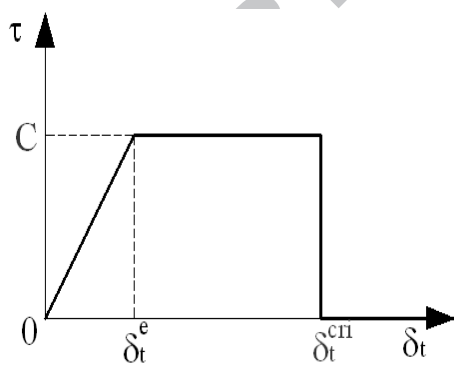
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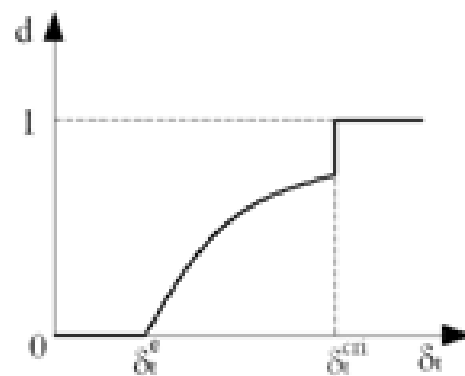
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Figures

Fig. 1



(a) Tangential stress-relative
Displacement relation



(b) Damage evolution

Fig. 2

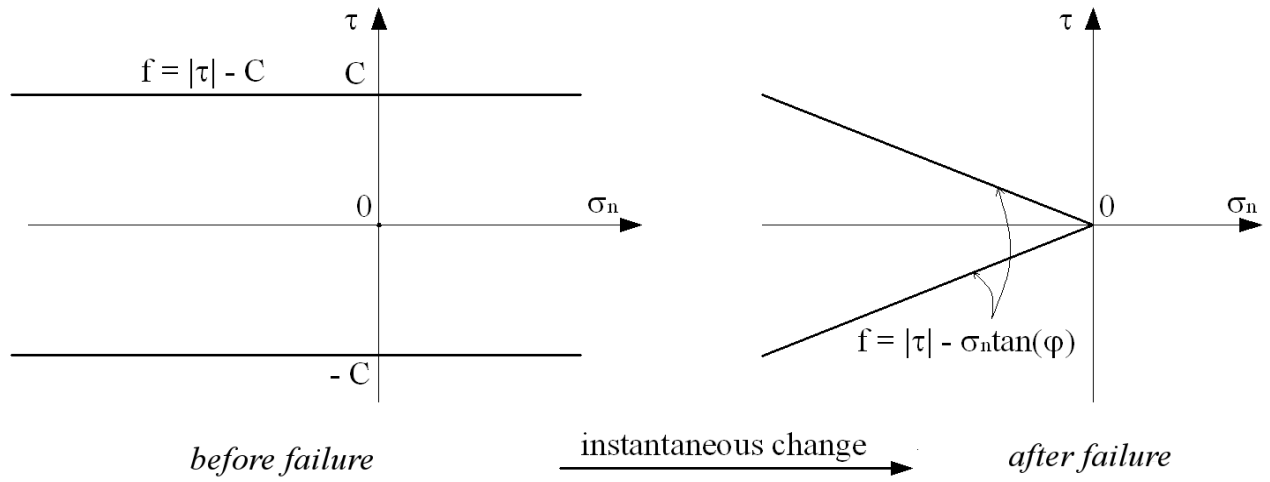


Fig. 3

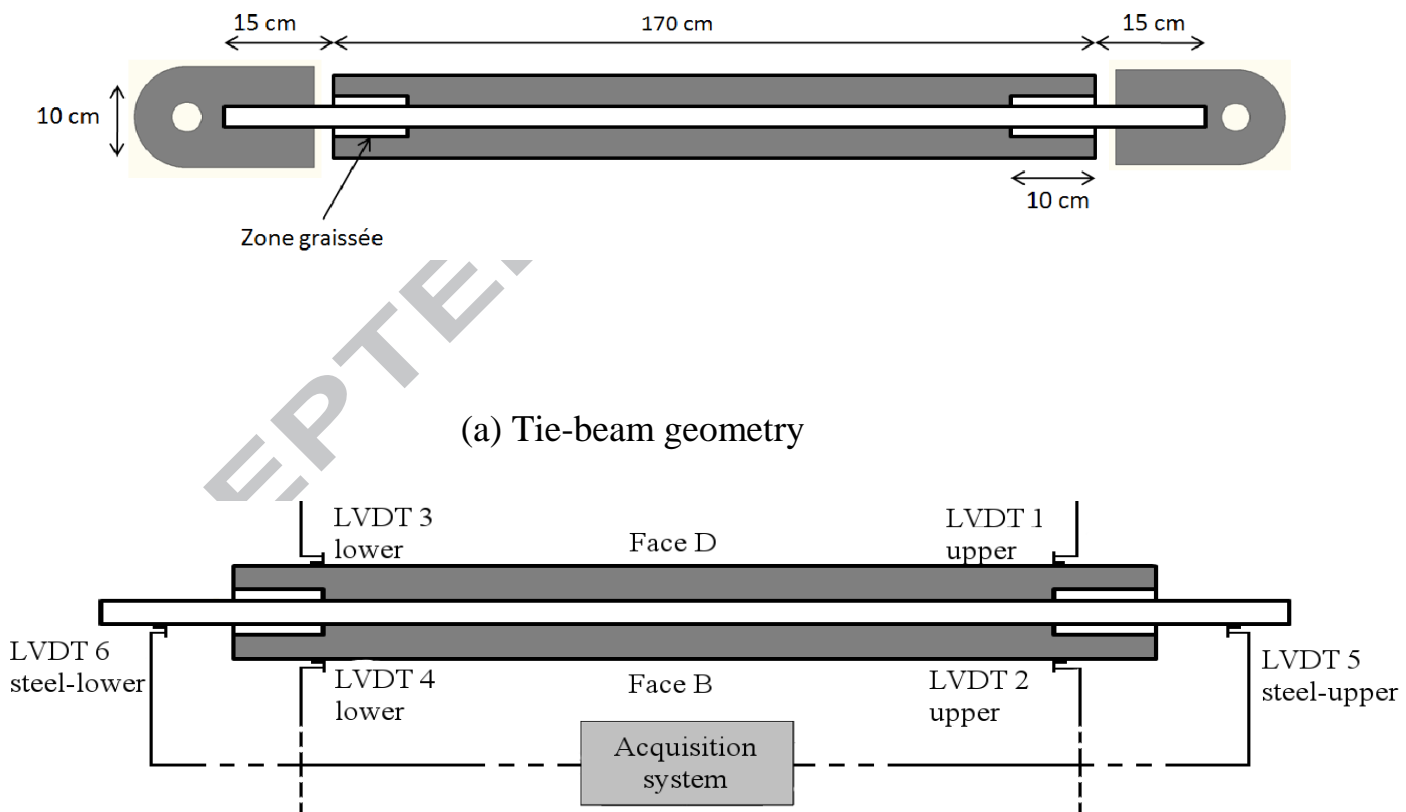


Fig. 4



Fig. 5

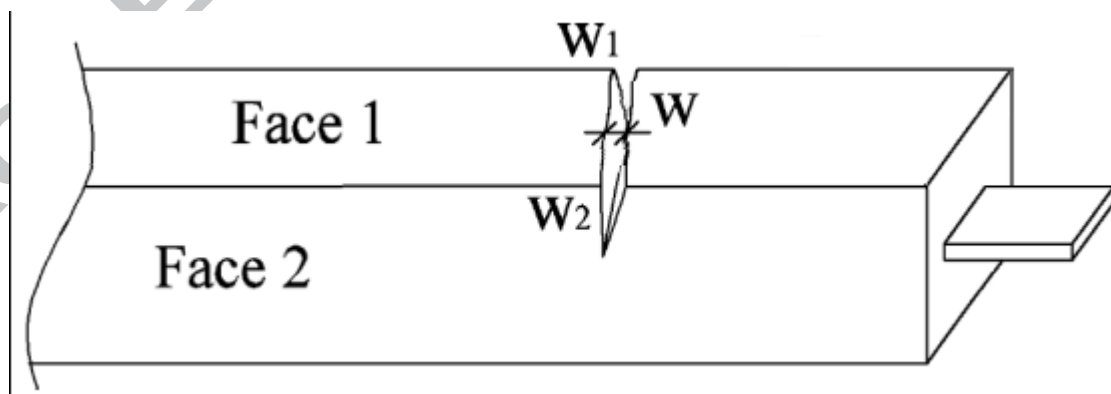


Fig. 6

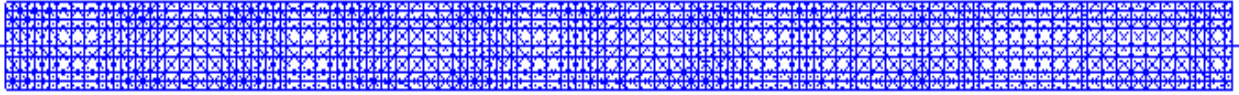


Fig. 7

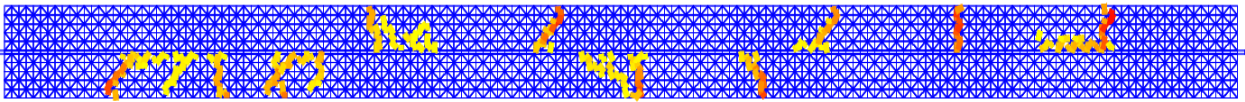


Fig. 8

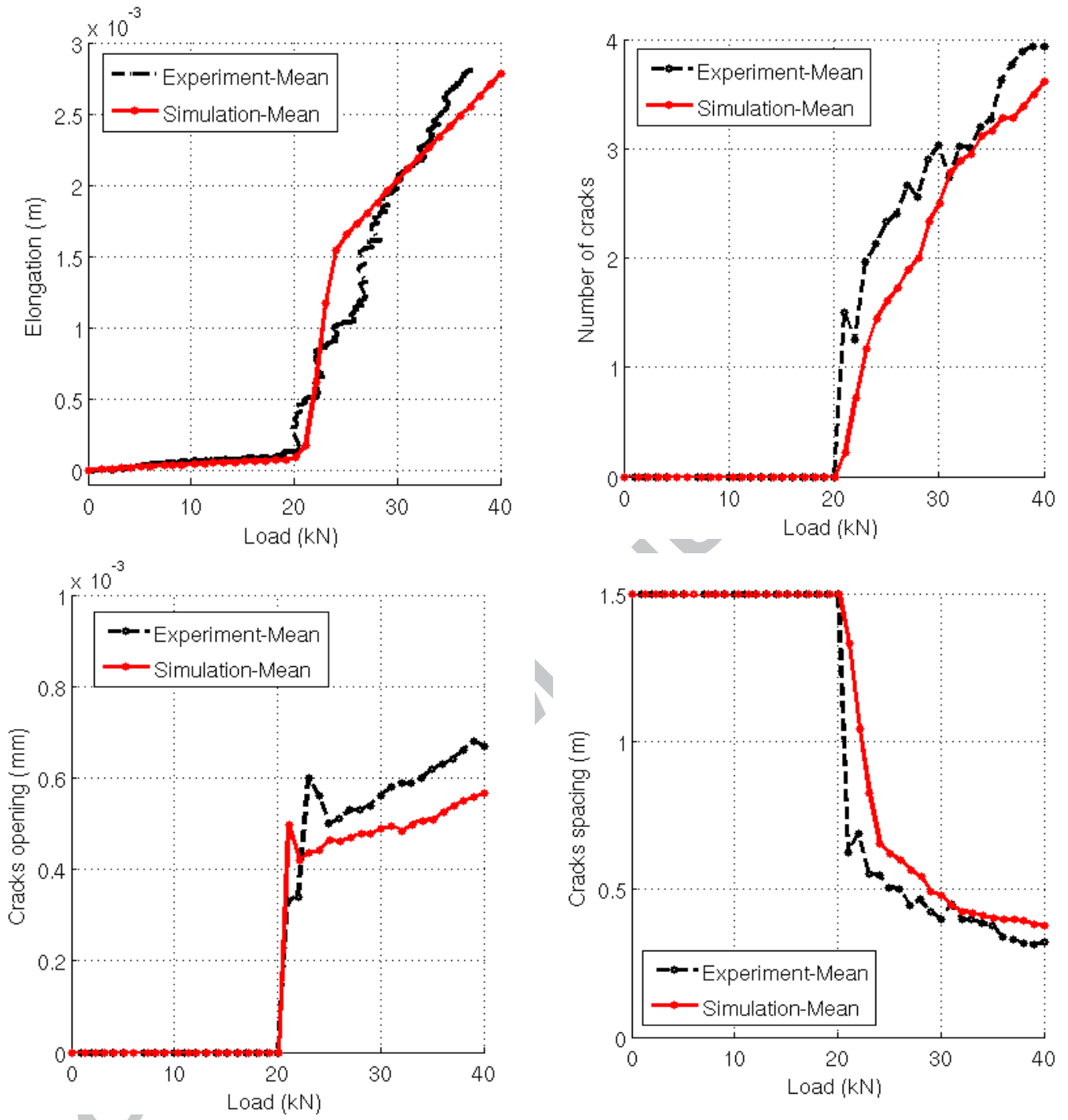


Fig. 9

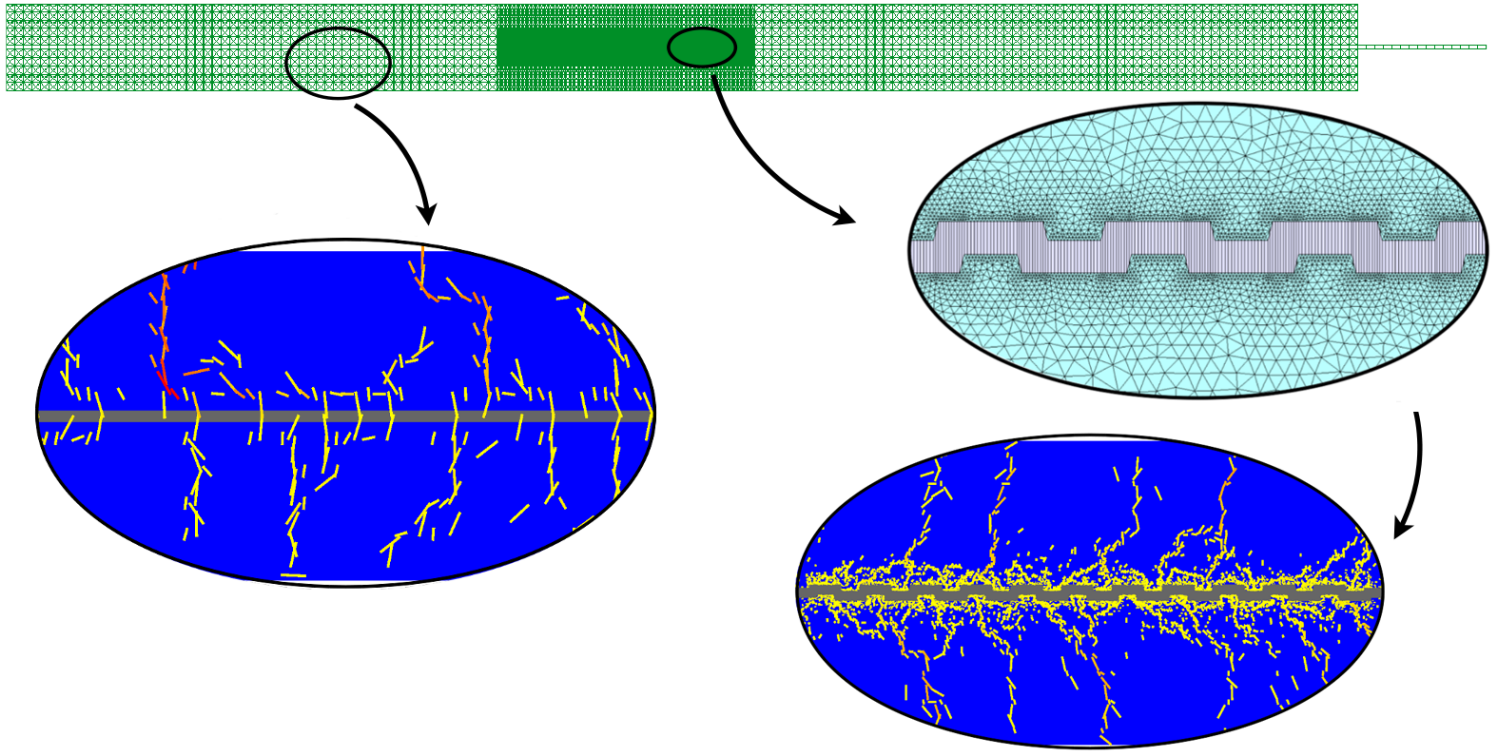


Fig. 10

ACCEPTED MANUSCRIPT

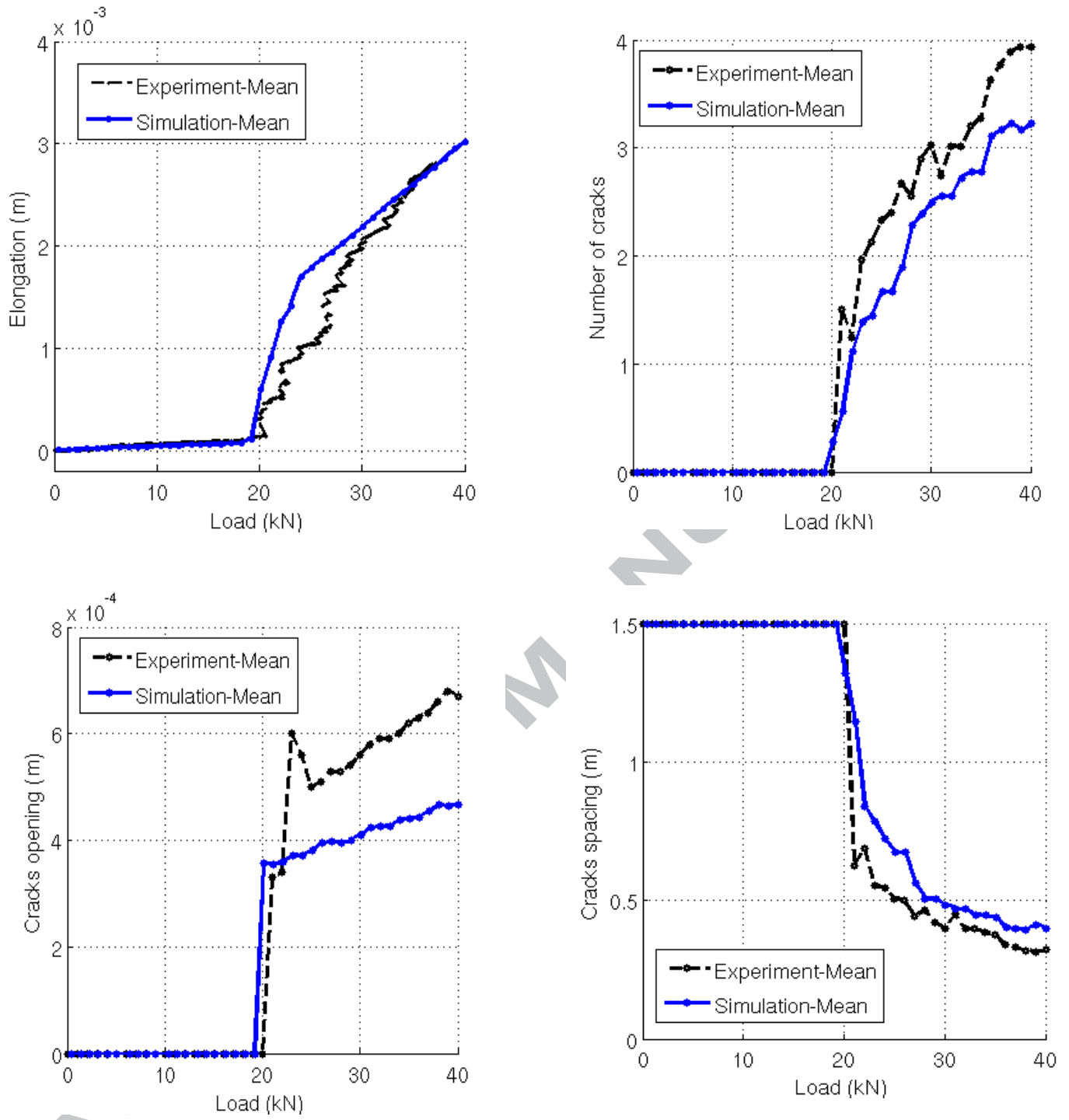


Fig. 11

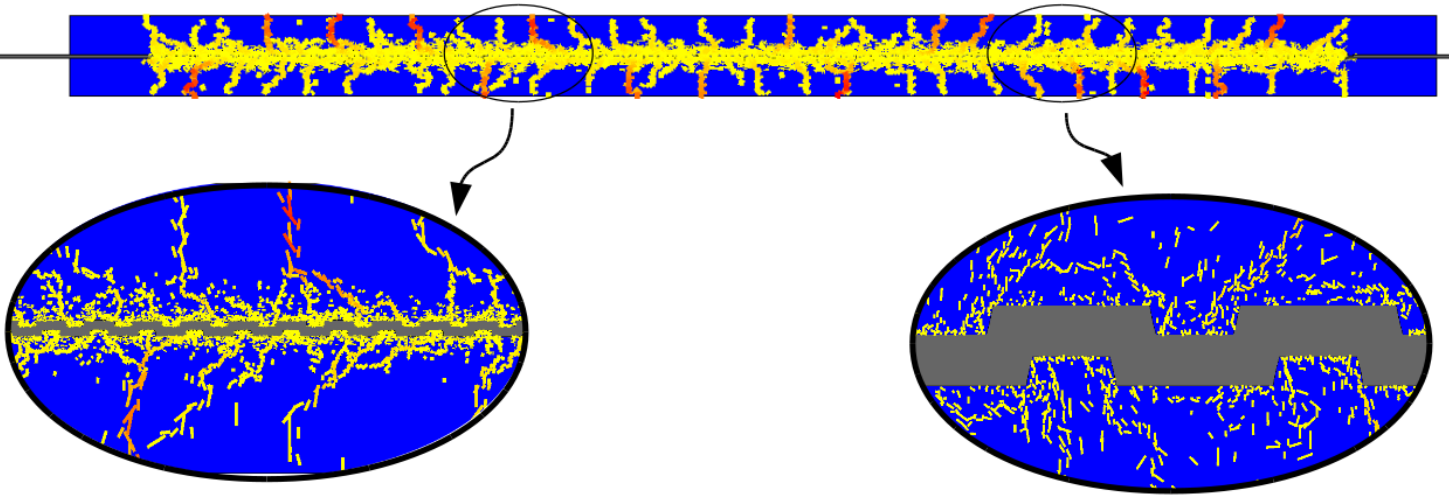


Fig.12

ACCEPTED MANUSCRIPT

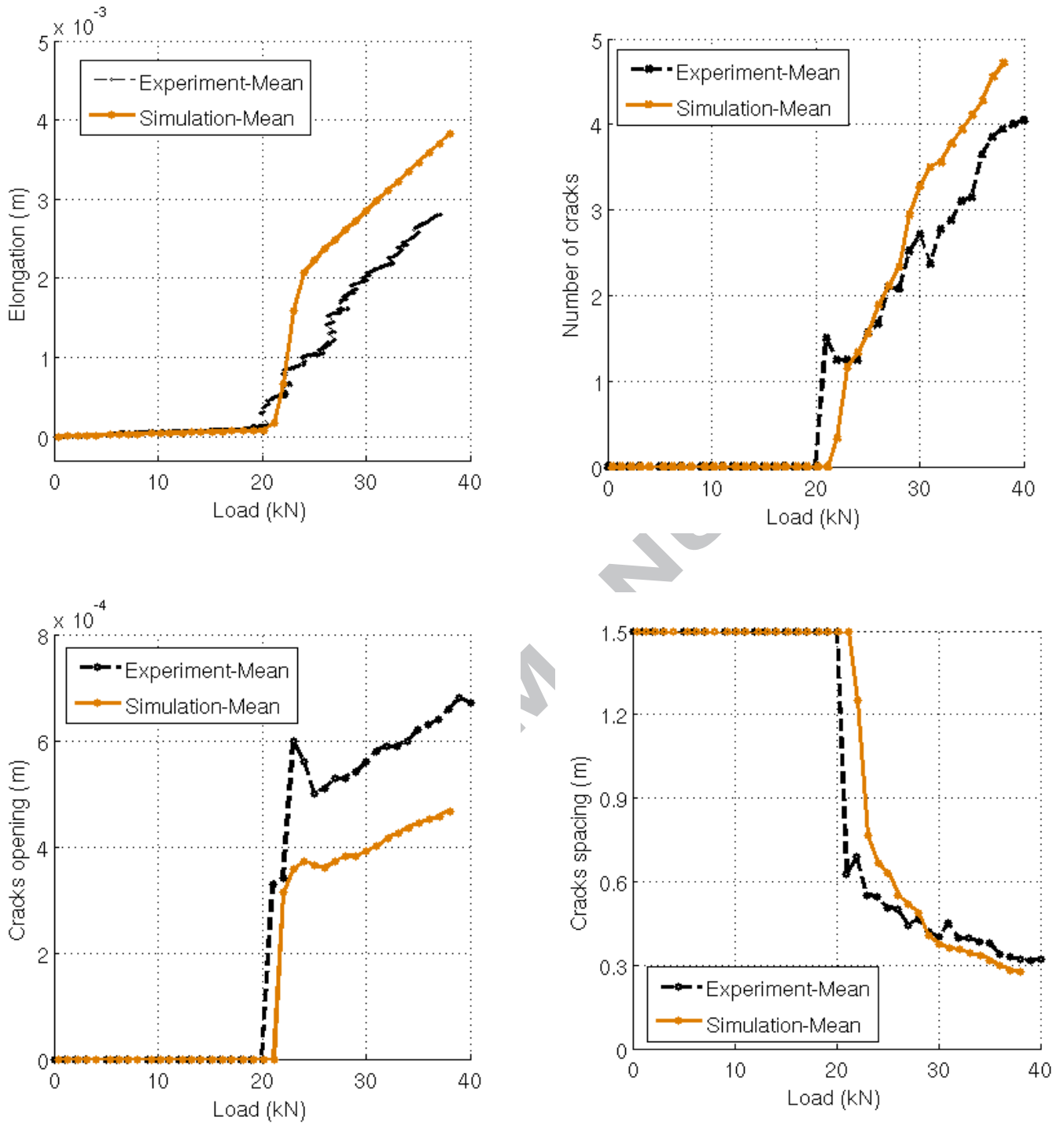


Fig. 13

List of tables

Table 1. Composition of the concrete (per m³).

Contituents	Weight in kg
Sand 0/4	743
Gravel 4/10	340
Gravel 10/16	752
Cement CEMI 52.5	400
Superplasticizer	2.6
Water	165
Total	2402.6

Table 2: Material characteristics considered in the numerical simulations

Models	Parameters	Values	Unit
Concrete	Compressive strength, f_c	53	MPa
	Young's modulus, E_c	32000	MPa
	Maximum aggregate size, D_g	0.016	m
Steel/Concrete Interface	Cohesion, C	6, 10, 15, 20, 25, 30	MPa
	Critical tangential displacement, δ_t^{cri}	6, 10, 15, 20, 25, 30	μm
Flat steel	Young's modulus, E_s	210000	MPa