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A SIMPLE EXPERIMENTAL AND SIMULATION FRAMEWORK FOR THE DESIGN OF STEEL FIBER REINFORCED CONCRETE

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Abstract. Steel fiber reinforced concrete (SFRC) has proven to provide excellent mechanical performance in terms of increased strength, ductility and energy absorption capacity [1]. These enhancements are provided by bridging phenomena and multiple-cracking distribution [1]. The numerical simulation of its mechanical behavior cannot be carried out with standard commercial codes yet, and its numerical simulation is mostly limited to academic research.
With the goal of carrying out engineering design and optimization SFRC structures, this paper presents the implementation of an experimental and numerical framework for the design of structures by means of SFRC. The presented work is based on previous results by other authors in modelling SFRC by means of an efficient multilevel computational framework [2], in which interface elements characterizing the bridging and cracking phenomena [3] are embedded within pre-existing Finite Element Method (FEM) codes. This framework will be implemented and validated in existing in-house FEM codes and in an open-source FEM package. In parallel, adequate experimentation has been carried out to define input parameters [4] and, validate the numerical algorithm. Overall, the framework intends to provide a general guideline for the efficient design of SFRC structures.

1 INTRODUCTION

Fiber reinforced concrete is a composite material formed by a heterogeneous mix of concrete and fibers. Although steel is the most commonly used material in the manufacturing of fibers for most structural and non-structural purposes, other materials as polypropylene and glass are also used. The main advantage of steel fiber reinforced concrete (SFRC), in regard to its mechanics, is its postpeak behavior [5]. Steel fibers change the way concrete fractures, translating it from brittle fracture to ductile fracture and hence, providing interesting energy absorption capacities. The exhibited ductility will rely upon the amount of fibers and its properties, matrix strength and their interaction [6].

Despite the clear enhancements provided by SFRC respect to more traditional concrete options, it is still rarely seen in structural design. One of the main reasons is its mechanical complexity, combined with a lack of clear design normative and guidelines. Because of that, SFRC use is still limited to specific applications, in which advanced consultancy and experimentation are justified. In terms of simulation, available commercial codes do not provide models that can accurately describe SFRC behavior. On the other hand, more advanced academic codes are still limited to scientific research due to its still large computational cost, which makes them unpractical for real-life applications.

The complexity behind the numerical simulation of SFRC mechanics is due to several reasons. Firstly, the heterogeneity of concrete itself and the difficulty to capture crack propagation in an efficient and accurate way. Next, capturing the postpeak behavior caused by the fibers bridging effect is a phenomenal modeling challenge due to its mesoscale nature. Fibers essentially arrest any advancing cracks by applying punching forces at the crack tips, thus delaying their propagation across the matrix [7]. The wide variability of fibers and concrete types make difficult to quantify the bridging effect with a simple numerical tool. Furthermore, the unknown distribution within the concrete element also adds complexity to the simulation [8]. Fibers are mixed and randomly distributed, thus, making very difficult to extend the debonding-law of one unique fiber to group behavior [8]–[11].

With the final objective of achieving a numerical tool for the design and optimization of SFRC structures, the current paper proposes the development of an experimental and numerical framework to be used in a routine manner for the design of SFRC structures. Having reviewed previous research about SFRC simulation, intermediate elements [3] have been chosen as a way to introduce the bridging effect. These intermediate elements will be located between the concrete elements and their behavior will be described with a debonding-law [10] [12]. The FEM will be implemented in an efficient numerical algorithm for the dynamic simulation of fiber reinforced concrete in real-life applications, ready to use for the design of concrete structures. The new algorithm will be implemented within the open-source framework Florence (https://github.com/romeric/florence), developed at Swansea University (UK). In parallel, adequate experimentation will be carried out at Universidad de Burgos (Spain), which will allow the validation of the simulation framework. This approach is aligned with the philosophy of a technology center, as Tecnalia Research & Innovation, which transfer the knowledge developed in universities to real applicability.

The steps that will be taken to simulate the behavior of a real element are described in Figure 1. Firstly, the mechanical properties, that will feed the constitutive model of the materials and simulate the mechanical phenomena, should be characterized. Most of the testing to be carried out are well defined because they are very commonly used. However, some needed inputs, for instance tensile strength of concrete, are not widely used and there is not so much experience in its characterization. This feature will hamper the determination of the testing campaign. Once the inputs are defined, the numerical results calculated through finite element model (FEM) might be validated with experimental results.

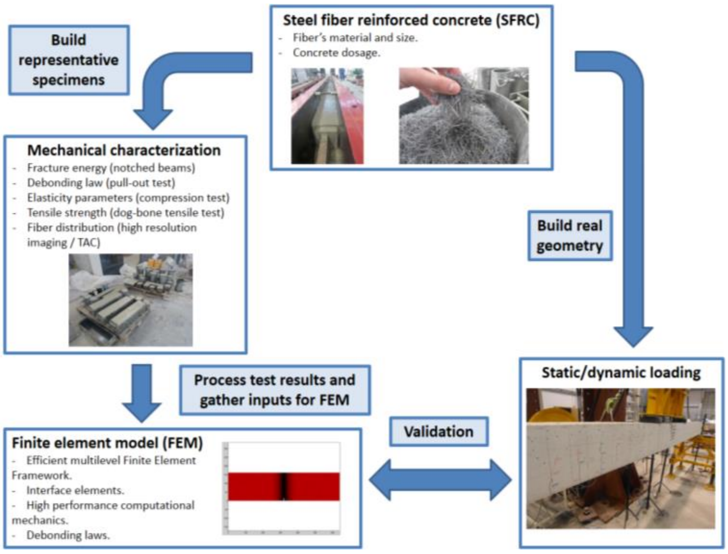

Figure 1: Overall strategy

2 NUMERICAL IMPLEMENTATION

The modelling of FRC has traditionally been carried out by using cracking models for plain concrete, with a modification of the post-peak regime of the constitutive law to include an increase on residual stress and fracture energy, which represent the enhanced ductility of FRC at a phenomenological level. Despite this option may produce satisfactory results in terms of the global behavior of a structure, it cannot reproduce crack propagation phenomena and, therefore, it is not adequate for the optimization of fiber reinforcement distribution within a concrete structure.

In terms of a more accurate simulation of FRC behavior, several options can be found in literature. Among them, one can find phase field methods, XFEM, explicit representations of the fibers and discrete approaches such as Latice Boltzman. Yet, most of these approaches require their specific implementation and cannot take advantage of pre-existing Finite Element frameworks or have a very high computational cost, both in terms of resources and time. An interesting approach which gives very satisfactory results as compared to experiments, and can be implemented within a pre-existing FEM framework is the multi-level approach proposed in [4], which is based in the high aspect ratio finite elements for crack propagation as proposed in [13]. In this framework, a set of high aspect ratio interface elements are inserted within the FEM mesh, which can reproduce the crack propagation phenomena through a tension damage model Figure 2. In [4], this tension damage law is replaced by a bridging law, which characterize the pull-out behavior of the fiber cocktail as a function of the embedded length and insertion angle.

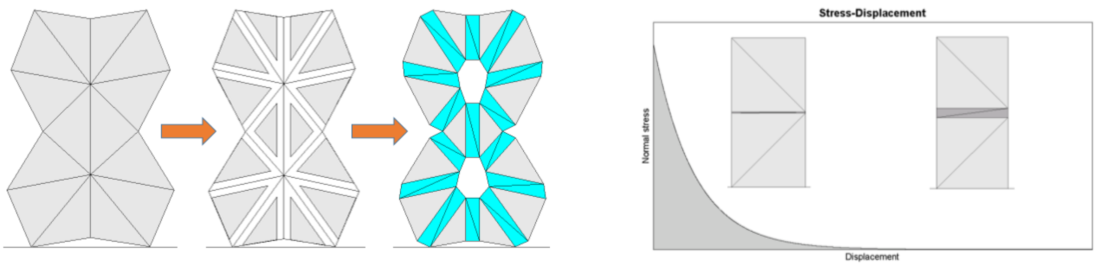

Figure 2: Intermediate elements (left) and a simple tension damage model (right)

Intermediate elements will be defined by tension damage model, where the effective stress normal to the base of the element ($\bar{\sigma}_{nn}$) and internal variables (r) defines the damage criterion. The normal component of the stress (σ_{nn}) is deducted from the constitutive relation, where d is damage variable, $\mathbb{C}$ is the elastic tensor, ε is the strain, $\bar{n}$ is the normal vector and $\bar{\sigma}$ the effective stress.

$$\sigma = (1-d)\,\mathbb{C} : \varepsilon = (1-d)\,\bar{\sigma} \tag{1}$$

$$\sigma_{nn} = \bar{n} \cdot \sigma \cdot \bar{n} \tag{2}$$

$$\bar{\sigma}_{nn} - r \leq 0 \tag{3}$$

Thus, damage is defined in terms of internal variables and assumed softening law (q). In this example, it has assumed exponential softening law:

$$q(r) = q_0\, e^{A\,h\left(1-\frac{r}{q_0}\right)} = f_t \cdot e^{\frac{f_t^2}{G_f E}\,h\left(1-\frac{r}{f_t}\right)} \tag{4}$$

$$d = 1 - \frac{q(r)}{r} \tag{5}$$

where f_t is the tensile strength, G_f is the fracture energy, E is Young's modulus, h is height of the intermediate element, with $q_0 = f_t$.

In this paper, the multilevel framework for the simulation of the cracking phenomena in fiber reinforced concrete will be implemented within an open-source, efficient Finite Element simulation framework, Florence, implemented at Swansea University by Dr. Roman Poya. Florence is a Python based computational framework for integrated computer aided design, by means of finite element methods for linear and nonlinear analysis of solids, fluids and coupled electro-mechanical systems. The core of the software is optimized via a specific data parallel tensor library, named Fastor [2], which allows for simulation by means of High Performance Computing (HPC). We believe that by implementing a reliable and robust algorithm for the simulation of FRC within a powerful computational framework such as Florence, will allow studying a wide variety of complex real-life phenomena occurring in FRC, as well as the virtual prototyping of FRC structures in the upcoming future. Further to that, the implementation within an open-source framework will make the developments available to the research community.

3 MECHANICAL CARACTERIZATION

A series of tests have been carried out at Universidad de Burgos to obtain the necessary parameters that characterize concrete and fibers and that will be used as an input in the FEM framework (see).

Table 1: Mechanical characterization and validation tests

MATERIAL	PROPERTY	TESTING	USE
Concrete (matrix)	Young's modulus	Compression test	Constitutive behavior
	Poisson´s ratio	Compression test	Constitutive behavior
	Compression strength	Compression test	Constitutive behavior
	Tensile strength	Dog-bone or notched-beam tensile test	Constitutive behavior
	Fracture energy	Dog-bone or notched-beam tensile test	Constitutive behavior
Steel fiber	Young's modulus	Technical sheet	Bridging effect
	Poisson's ratio	Technical sheet	Bridging effect
	Tensile strength	Technical sheet	Bridging effect
	Debonding-law	Pull-out test	Bridging effect
	Fiber distribution	TAC/Image processing	Bridging effect
Composite	Tensile strength	Dog-bone tensile test	Validation
	Fracture energy	Notched-beam tensile test	Validation
	Overall behavior	Four-point flexural test	Validation

The tension damage model of concrete requires obtaining Young's modulus, Poisson's ratio, compressive strength, tensile strength and fracture energy. The first three are used to model the elastic branch of the material calculated through a normalized compression test. On the other hand, the tensile strength and fracture energy are needed to model the post-peak behavior (strain softening branch). Following previous research [1], [14], it has been opted for Dog-bone tensile test (see Figure 3) and notched-beam test to define the needed inputs.

Figure 3: Dog-bone samples

Fibers elastic properties are specified in the technical sheets provided by the supplier. On the other hand, the interaction between concrete and fiber, defined through the debonding law, plays a key role and needs to be obtained using a pull-out test. This test (see) will give the pull-out force-crack opening relationship of a single fiber loaded parallel to the direction of the fiber [15]. The parameters of a specific analytical debonding law will be curve-fitted using the results of these tests. From those parameters, the behavior can be extrapolated to every loading direction [12] and to other geometries, such as hook-ended fibers [10].

The distribution of the fibers within the concrete matrix has a random nature due to its high dependence to the casting procedure. Image processing technique and TACs will be used to build up distribution functions [16], which would describe the orientation and location of fibers.

Figure 4: Pull-out test

4 VALIDATION AND RESULTS

The validation of the algorithm will be carried in two phases. Firstly, literature results and synthetic problems will be used to ensure that the numerical algorithm has been implemented in the right direction. Next, a series of experimental tests with increased degree of complexity will be carried out in laboratory environment. The numerical algorithm, which will use the input parameters defined in the previous section, will be validated against these experimental results.

As first steps towards this implementation, the algorithm has been tested in Matlab for several benchmark problems found in literature. Figure 3 illustrates an example of a notched three-point bending beam, which is numerically analyzed to predict the crack pattern. The interface element FEM mesh is shown in Figure 3.

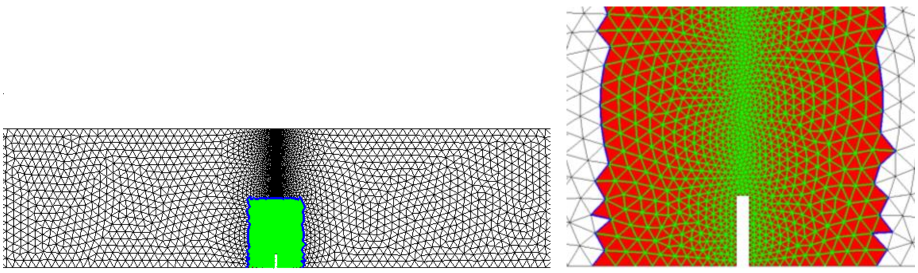

Figure 5: Three-point bending beam

Figure 5 shows the results calculated from a tensile test. It can be seen that intermediate elements located at the center are strongly deformed. In the printed curves all elements followed the same law as it can be seen. However, some intermediate elements are not as damaged as them and the softening range is not so developed.

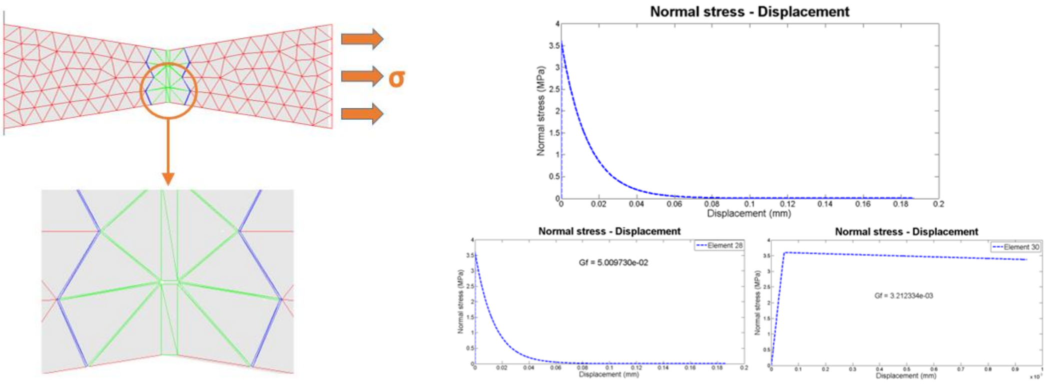

Figure 6: Tensile test (left) and stress-displacement curves of intermediate elements (right)

Once the behavior of fibers is numerically sound, elements with increasing complexity will be tested to broaden the applicability (see). Firstly, the numerical tool will be validated with small size elements, such as dog-bone test, in which the crack initiation and propagation is known to occur in the middle section of the specimen. Next, a notched beam [17] will be used, where the uncertainties surrounding fiber location will have increased due to the casting process. The cracking procedure and the bridging phenomenon have been partially bounded through the notch.

Figure 7 shows the structural response of a notched beam [3]. As can be noted in the load-displacement curve, experimental and numerical responses are in good agreement. It is also shown cracking and damage development at different stages. The crack starts at the notch and it will grow until the failure of the beam. Stress concentration at middle part of the beam shows the tip of the crack. The stress concentration will be close to the notch at the beginning. After reaching the maximum load, the strain of intermediate elements has increased faster and the stress concentration referred before are closer to the top part of the beam. At the failure, intermediate elements are fully damaged and distorted.

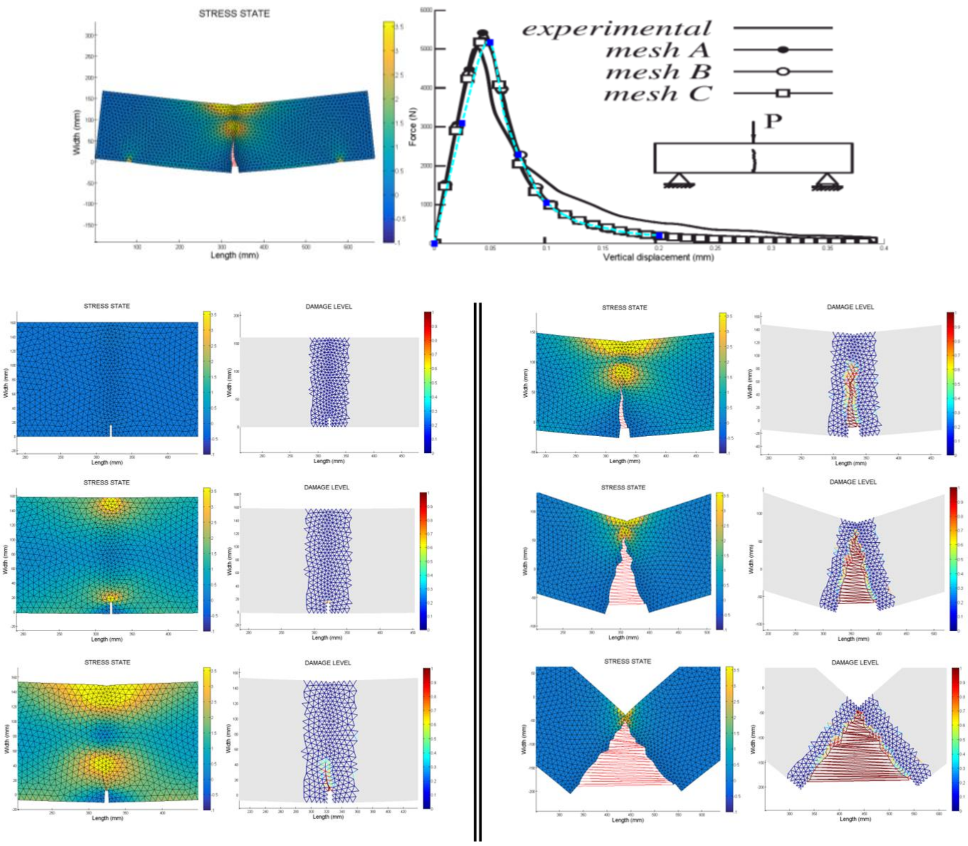

Figure 7: Three-point bending beam (a) Force-displacement curve [3] (b) Crack propagation

Finally, the interaction fiber-traditional reinforcement will be studied through two four-point flexural test (Figure 8). Two identical beams have been built to study the difference between SFRC and traditionally reinforced beams. Both beams are identical except for the type of reinforcement (SFRC vs RC). The beams have been designed to fail at tension and thus facilitate the validation of the crack propagation model.

Figure 8: Four-point flexural test carried out at Universidad de Burgos

5 CONCLUSIONS AND FUTURE WORKS

The proposed methodology (see) aims to be a simple and accurate framework to calculate real-life SFRC structures. To this end, interface elements will be implemented within an efficient academic open-source environment. In parallel simple mechanical characterization of SFRC components has been done in the laboratory of the Universidad de Burgos. Lastly, the numerical algorithm will be validated with more realistic SFRC elements, such as the four-point bending beam.

As a first step, interface elements have been implemented within an in house Matlab FEM code. These intermediate elements' behavior has been studied through hardening-softening laws. Afterwards, bridging forces will be added to the code. On the other hand, and in order to characterize the debonding mechanism from pull-out tests, semi empirical bon-slip model as the ones in [18] [10] [19] has already been implemented in Matlab codes. From this debonding-laws, fiber's group-behavior will be defined along with the density functions of fibers distribution and orientation.

Regarding the experimentation (Table 1), mechanical characterization has been carried out at the Universidad de Burgos. They should be sufficiently representative and accurate for the purpose of the application. This point will be especially difficult for the definition of fibers orientation and distribution due to the incapacity to see within the concrete element. Concrete's properties definition is normalized and they have been easily defined.

Future work will be carried out in larger elements (beams) to enlarge the scope of the application.

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References

[1] K. Wille, S. El-Tawil, and A. E. Naaman, "Properties of strain hardening ultra high performance fiber reinforced concrete (UHP-FRC) under direct tensile loading," *Cem. Concr. Compos.*, vol. 48, pp. 53–66, 2014.

[2] R. Poya, A. J. Gil, and R. Ortigosa, "A high performance data parallel tensor contraction framework: Application to coupled electro-mechanics," *Comput. Phys. Commun.*, vol. 216, pp. 35–52, Jul. 2017.

[3] O. L. Manzoli, M. A. Maedo, L. A. G. Bitencourt, and E. A. Rodrigues, "On the use of finite elements with a high aspect ratio for modeling cracks in quasi-brittle materials," *Eng. Fract. Mech.*, vol. 153, pp. 151–170, 2016.

[4] Y. Zhan, "Multilevel Modeling of Fiber-Reinforced Concrete and Application to Numerical Simulations of Tunnel Lining Segments," 2016.

[5] J. A. O. Barros, V. M. C. F. Cunha, A. F. Ribeiro, and J. A. B. Antunes, "Post-cracking behaviour of steel fiber reinforced concrete," 2004.

[6] P. Robins, S. Austin, and P. Jones, "Pull-out behaviour of hooked steel fibres," *Mater. Struct. Constr.*, vol. 35, pp. 434–442, 2002.

[7] A. Jansson, “Effects of Steel Fibres on Cracking in Reinforced Concrete,” *Chalmers Repro Serv. Gothenbg.*, 2011.
[8] J. M. Torrents, A. Blanco, P. Pujadas, A. Aguado, P. Juan-García, and M. Á. Sánchez-Moragues, “Inductive method for assessing the amount and orientation of steel fibers in concrete,” *Mater. Struct.*, vol. 45, no. 10, pp. 1577–1592, Oct. 2012.
[9] F. Laranjeira *et al.*, “Predicting the pullout response of inclined straight steel fibers,” *Mater. Struct.*, vol. 43, pp. 875–895, 2010.
[10] F. Laranjeira, C. Molins, and A. Aguado, “Predicting the pullout response of inclined hooked steel fibers,” *Cem. Concr. Res.*, vol. 40, pp. 1471–1487, 2010.
[11] F. Laranjeira, S. Grünewald, J. Walraven, C. Blom, C. Molins, and A. Aguado, “Characterization of the orientation profile of steel fiber reinforced concrete,” 2010.
[12] C. V.M.C.F., B. J.A.O., and C. J.S., “Pullout behaviour of hooked-end steel fibres in self-compacting concrete,” 2007.
[13] O. L. Manzoli, A. L. Gamino, E. A. Rodrigues, and G. K. S. Claro, “Modeling of interfaces in two-dimensional problems using solid finite elements with high aspect ratio,” *Comput. Struct.*, vol. 94–95, pp. 70–82, 2012.
[14] K. Wille, J. Dong, Kim, and A. E. Naaman, “Strain-hardening UHP-FRC with low fiber contents,” *Mater. Struct.*, 2010.
[15] A. E. Naaman, G. G. Namur, J. M. Alwan, and H. S. Najm, “Fiber pullout and bond slip. I: Analytical study,” 1991.
[16] B. Y. Lee, S.-T. Kang, H.-B. Yun, and Y. Y. Kim, “Improved Sectional Image Analysis Technique for Evaluating Fiber Orientations in Fiber-Reinforced Cement-Based Materials,” 2015.
[17] J. A. Fuente-Alonso, V. Ortega-López, M. Skaf, Á. Aragón, and J. T. San-José, “Performance of fiber-reinforced EAF slag concrete for use in pavements,” *Constr. Build. Mater.*, vol. 149, pp. 629–638, 2017.
[18] M.Sc. Yijian Zhan, “Multilevel Modeling of Fiber-Reinforced Concrete and Application to Numerical Simulations of Tunnel Lining Segments,” no. November, 2016.
[19] V. M. C. F. Cunha, J. A. O. Barros, and J. M. Sena-Cruz, “Pullout Behavior of Steel Fibers in Self-Compacting Concrete,” *J. Mater. Civ. Eng.*, vol. Vol. 22, N, 2009.