



INTERACTIVE GRAPHICAL APPLICATION FOR MODELING REINFORCED CONCRETE STRUCTURES

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Abstract. *The advent of computer methods combined with the large amount of studies related to the structural engineering field, and, more specifically, related to structures in reinforced concrete, leads to the development of numerical models that improve the prediction of the behavior of these structures. Among several developed models, the models based on the Finite Element Method (FEM) have shown to be powerful tools for the analysis of reinforced, simple and pre-stressed concrete structures. In this context, the inclusion of the reinforcement in the analysis of reinforced concrete structures can be made using three different models: discrete reinforcement model, embedded reinforcement model and smeared reinforcement model. In the first two models, the phenomenon of bond-slip can be included, making them more realistic and, therefore, more popular. In this sense, this paper presents an interactive graphical application for modeling reinforced concrete structures by FEM, allowing to considering the bond-slip phenomenon. The reinforcement is incorporated through discrete model, with bond-slip phenomenon simulated by nodal springs or by contact elements. The INSANE system (INteractive Structural ANalysis Environment), a free software developed at the Department of Structural Engineering of the Federal University of Minas Gerais, is used in the implementation.*

Keywords: *Reinforced Concrete, Finite Element Method, Discrete and Embedded Reinforcement Models, Bond-Slip Phenomenon*

1 INTRODUCTION

The application of reinforced concrete structures is widespread and, from this use, merges the importance of the development of tools for the analysis of this type of structure. The analysis must take into account that the reinforced concrete is composed by two distinct materials, steel and concrete, conferring a more complex behavior to the system. Also, it needs to be considered the interaction between these two different materials, being this interaction defined by mechanism of adherence and bond-slip.

The application of models based on the Finite Element Method (FEM) have been providing good results for the analysis of several types of structures, including, in this context, the study of models that represent the steel reinforcing. There are three models that can treat this inclusion: the discrete reinforcement model, the embedded reinforcement model and the smeared reinforcement model, considering that the first two models allow the bond-slip phenomenon. This paper presents the present stage of the inclusion of tools in the graphic interface of INSANE system, to support the analysis of elements with the discrete reinforcement model, providing to the user options to consider or not the phenomenon of bond-slip.

The INSANE system (INteractive Structural ANalysis Environment), where this project is being held, is a free software implemented in Java, following the principles of object-oriented programming. INSANE was developed in the Structural Engineering Department in Universidade Federal de Minas Gerais and it can be downloaded at <http://www.insane.dees.ufmg.br/>. In the numeric core, the analysis of reinforced concrete structures was already developed in Castro (2013). Through the work here presented, it was possible to present a friendly-user interface to access this modeling, implementing an interactive graphical application.

In the next sections, will be detailed the interactive graphical applications of INSANE (Section 2), the reinforcement model applied in this paper (Section 3), the numeric models for the simulation of the bond-slip phenomenon (Section 4), the implementation of the graphical application (Section 5), as well as an example to simulate the process here presented (Section 6).

2 INSANE INTERACTIVE GRAPHICAL APPLICATIONS

According to Gonçalves (2004), three phases must be followed to develop an application based on the object-oriented programming. The first is the analysis phase, where the objects are defined and described, setting the problem scope. Following, the logic elements are delineated, characterizing the attributes and the methods involved, defining the project phase. In the last step the components are implemented in a programming language that allows the adoption of object-oriented system. For the interactive graphic applications of INSANE, the following tools were applied.

2.1 Software design patterns

The INSANE system has a structure in layers, according to Penna (2007), that result from the merging of three design patterns: the Model-View-Controller (MVC), the Observer, and the Command. In the MVC, the Model stores the model data, the View represents the model, and the Controller intermediate the communication between the view and the model. The observer

propagates the changes made in the model to the related View-Controller. At last, the Command organize all the commands required, packing them in separated classes. This process promotes the segmentation of the program, and it favors the expansion of it.

2.2 Data structure

Based on Silva et al. (2015), to propitiate the development of geometrical models, it is important to store the data in an organized and structured manner, where it can be easily accessed, accomplishing a less costly process. To achieve this goal, the graphic applications of INSANE put to use the half-edge data structure, where one edge is represented by two half-edges, each one storing the information from one vertex of the original edge.

According to Mäntylä (1987), this data structure is based in the following hierarchy: **Solid**, **Face**, **Loop**, **Half-Edge** and **Vertex**. Del Savio et al. (2004) proposed the inclusion of an intermediate level, the **Edge**, connecting directly the edge and the half-edge related. This hierarchy is displayed in Fig. 1.

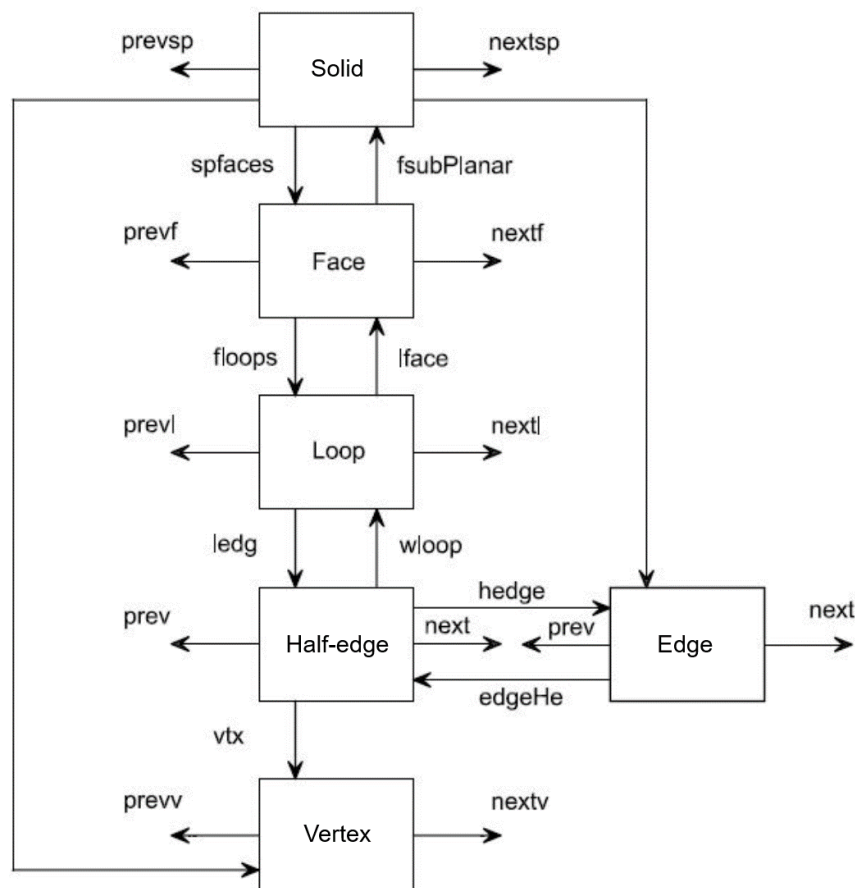


Figure 1: Half-edge data structure (Del Savio et al., 2004).

3 REINFORCEMENT MODELS

For the representation of steel reinforcement, three models can be utilized (Castro, 2013):

- Distributed reinforcement model;

- Discrete reinforcement model;
- Embedded reinforcement model.

The first model considers a distributed reinforcement, and it cannot include the analysis of the bond-slip phenomenon and changes in the geometry of the reinforcement layer. In the other hand, the discrete and the embedded reinforcement models allows the inclusion of the phenomenon, and, therefore, are more used and more robust. In this work, the discrete reinforcement model was applied, and it will be explained in Section 3.1.

3.1 Discrete reinforcement modeling

The first study that proposed the discrete reinforcement model was Ngo e Scordelis (1967), that considered a plane element to represent the concrete and a frame element for the steel reinforcement. Through this model, it can be included the bond-slip phenomenon, using special elements to connect the concrete and the steel elements. However, this model presents some limitations, because the position of the reinforcement is limited to the geometry of the mesh, as seen in Fig. 2. The description of the elements that creates the link between concrete and steel to include bond-slip will be exposed in section 4.

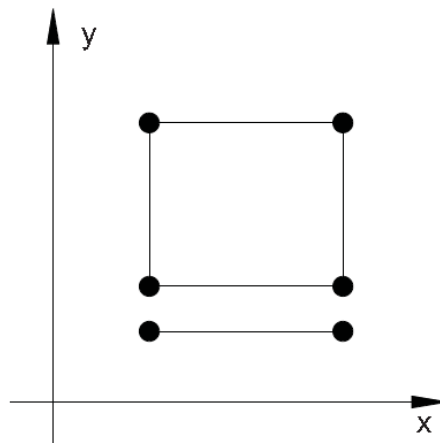


Figure 2: Bidimensional discrete reinforcement model (Castro, 2013).

4 NUMERIC MODELS FOR THE BOND-SLIP PHENOMENON

Generally, the modeling of reinforced concrete structures considers that concrete and steel have compatibility of strain, that is, there is a perfect adherence between the two materials. However, some situations require the inclusion in the analysis of a concrete-steel bond model (Castro, 2013). In a finite elements mesh, the connection between two adjacent elements is represented by the nodes that they share. This model do not propitiate the insertion of bond-slip phenomena, and, it becomes necessary the development of special elements that could represent the concrete-steel bond-slip. In this study, were applied two numeric models to simulate the phenomenon: nodal springs (Section 4.1), and contact elements (Section 4.2).

4.1 Nodal springs

Ngo e Scordelis (1967) proposed this model, where the phenomenon is represented by orthogonal springs without physical dimensions. These spring elements connect the steel nodes and the concrete nodes. The behavior in the interface of the two materials are defined by the relation stress-bond-slip chosen. This model is represented in Fig. 3, detailing the coordinated system of this model.

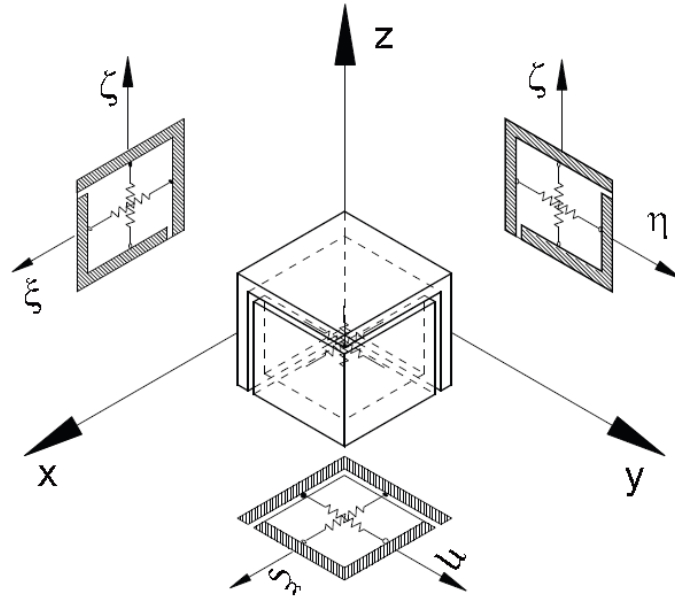


Figure 3: Spring model for three-dimensional and its coordinated system (Castro, 2013)

4.2 Contact elements

This model was first presented by Hoshino (1974) and Shafer (1975), and it proposes the use of a continuous element to represent the concrete-steel bond-slip. An example of a contact element with a linear approximation is shown in Fig. 4.

5 IMPLEMENTATION OF THE GRAPHICAL APPLICATION

The analysis of problems with steel reinforcement bars, allowing the possibility to include the bond-slip phenomenon, were only possible in INSANE through a XML (EXtensible Markup Language) file, that needed a well defined structure for its correct interpretation. The numerical implementation of the analysis was presented by Castro (2013), that implemented in the numerical core of the system the tools to the study of such problems. This work aims to develop a interactive graphical application that will support the modeling of these problems through the graphical interface of INSANE.

The modifications here implemented took place in the Preprocessing application of INSANE. The Preprocessing is a graphical interface connected to other two applications: the Processing, that represents the numerical core of the program; and the Postprocessing, that allows the graphical visualization of the results obtained by the processing application. The Preprocessing is based in the design pattern described in Section 2.1, and is divided in three modules:

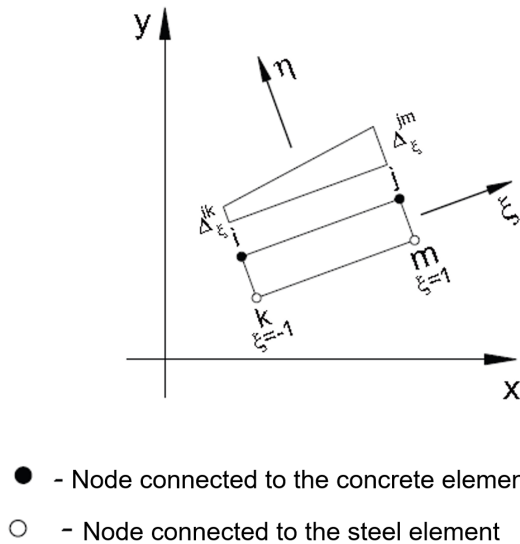


Figure 4: Contact element with linear approximation (Castro, 2013).

Geometry module, where the geometry of the problem is defined; *Mesh* module, where the geometry is discretized; and the *Attributes* module, where the attributes of the model are specified, as the constitutive model, the materials, the section and the boundary conditions.

6 EXAMPLE

To illustrate the analysis process through the interactive graphical application implemented, it was simulated the test carried by Elwi e Hrudehy (1989) and adapted in the work of Castro (2013). This problem involves the analysis of a quarter ring with one reinforcing layer, as illustrated in Fig. 5.

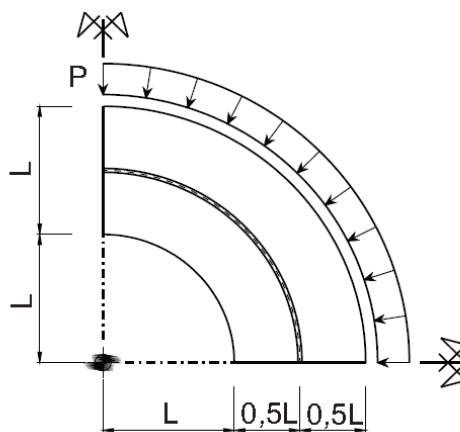


Figure 5: Quarter ring with one reinforcing layer (Castro, 2013).

Initially, the analysis was carried disregarding the bond-slip phenomenon, and, secondly, considering the phenomenon with a linear behavior, using nodal springs (Section 4.1) and contact elements (Section 4.2). In all the cases, the problem was modeled using 12 plane elements with one discrete reinforcing layer, and linear-elastic materials.

In the INSANE system, after defining the directory where the model will be saved, it is drawn the geometry of the problem through the *Geometry* module, as shown in Fig. 6. In this example, was considered $L = 1\text{m}$ (Fig. 5), and the mesh was built in the *Mesh* module, as is can be seen in Fig. 7.

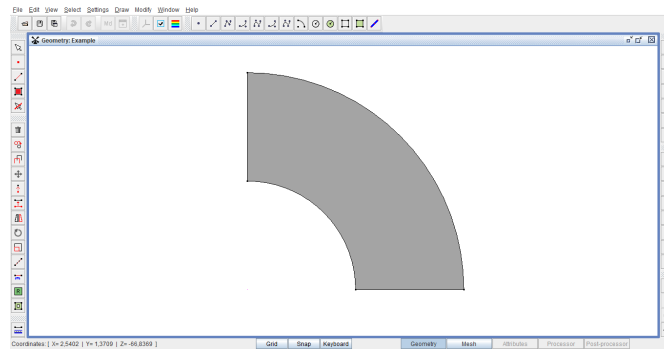


Figure 6: Definition of the geometry.

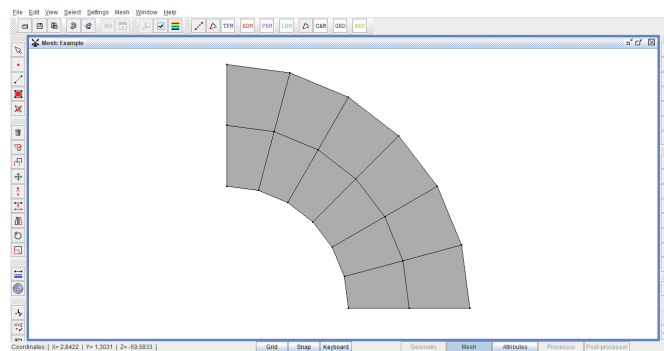


Figure 7: Definition of the mesh.

After this stage, it is defined the analysis in plane stress, and the definition of the shape of the finite elements as quadrilateral with eight nodes (Q8). Carrying the analysis to the *Attributes* module, it is defined the constitutive model, the materials, the sections, and the boundary conditions (Fig. 8). In this module, it was implemented the possibility to include steel reinforcing bars, and the bond-slip phenomenon.

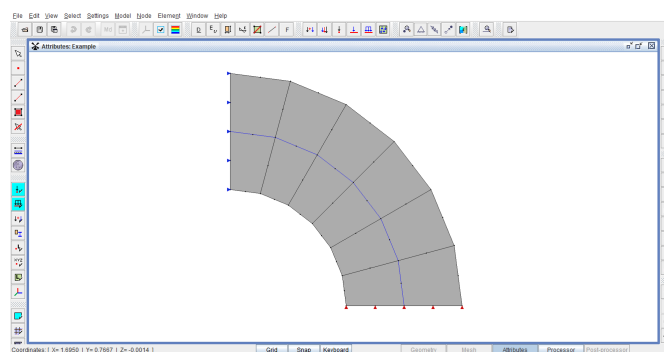


Figure 8: Attributes module.

The creation of steel reinforcement bars is allowed through the keyboard and through the mouse. If the keyboard option is selected, when the button for the bars creation is pushed, the

dialog shown in Fig. 9 is displayed, where the user has the option of creating bars selecting two vertices or based on one existence edge. If the keyboard option is not selected, the user can select the vertices or the edges for the creation of the bars.

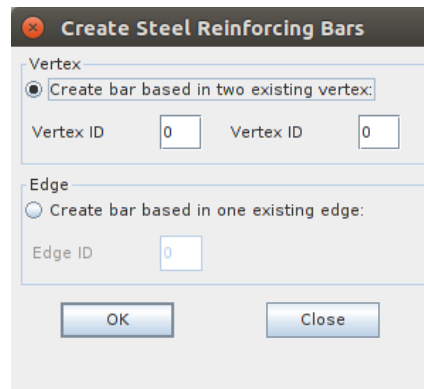


Figure 9: Dialog for the creation of the reinforcing bars.

To consider the bond-slip phenomenon, the user must create a specific material through the dialog that allows the definition of the materials involved in the analysis (Fig. 10). If the phenomenon is simulated by contact elements, the user must fill the fields *area*, associated with the contact element, and *elasticity*, that represents the elasticity of the steel bar. In the other hand, if the nodal spring will be used, the fields related to the elasticity, the spring angle and the influence area of the spring must be filled. For both cases, the user have to also define the bond law.

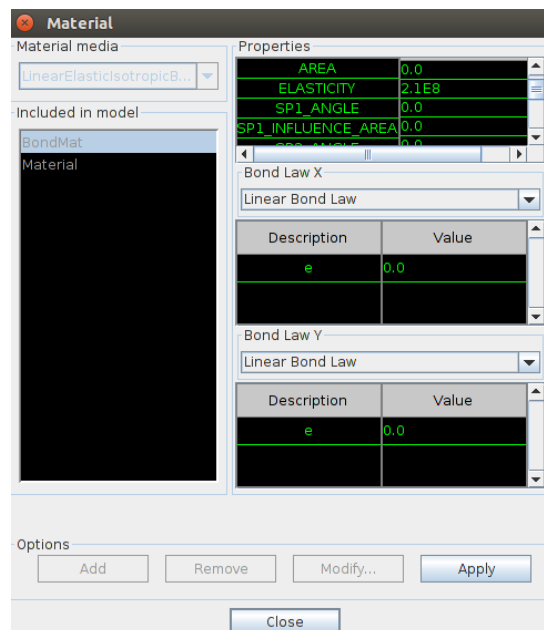


Figure 10: Dialog for the creations of the materials.

After defining all the attributes required for the analysis, the processing takes place, and the results can be visualized in the *Postprocessing* application, as illustrated in Fig. 11 where it is shown the deformed shape of the problem in the analysis where the bond-slip phenomenon was simulated by nodal springs.

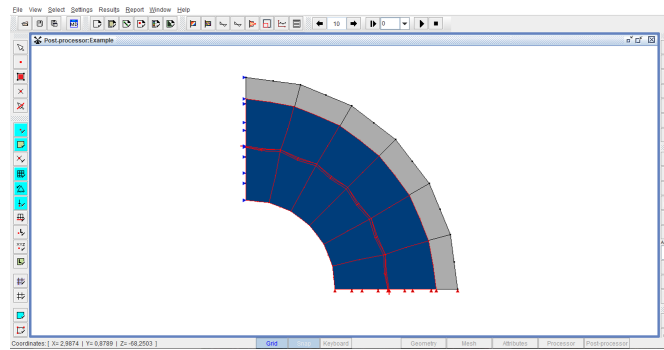


Figure 11: The deformed shape visualized in the *Postprocessing* application.

In this study, were processed three analysis for the same problem (Fig. 5): disregarding the bond-slip phenomenon, with the phenomenon simulated by nodal springs, and simulated by contact elements. The parameters for the modeling were: $A_s/L = 0.025$, $E_s/E_c = 8$, and $\nu = 0.25$. The results for the simulation are shown in Fig. 12 in a graph that compares the values obtained for the steel stress for the three analysis.

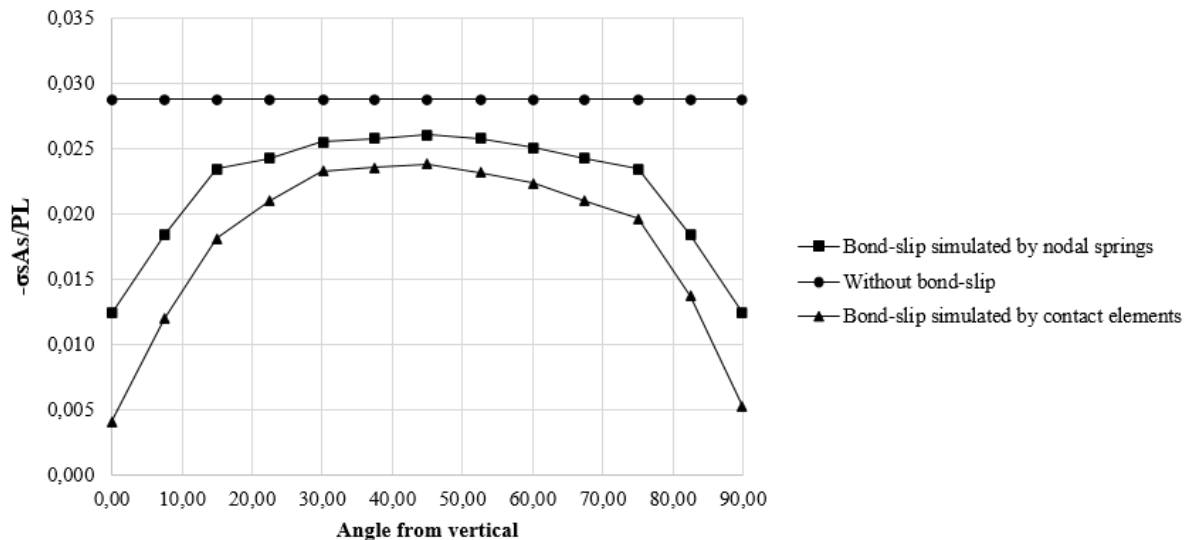


Figure 12: Steel stress, one-layer quarter ring problem.

CONCLUSIONS

The analysis of problems considering steel reinforcing bars, and with the possibility of the inclusion of the bond-slip phenomenon was implemented in the numerical core of INSANE in the work of Castro (2013), but it was only possible through a XML file, that requires a well defined structure for its interpretation. In the present work, it was presented the development of a interactive graphical application for this analysis, allowing the definition of the problem through a user-friendly interface. In the Preprocessing application were provided interactive tools for the inclusion of steel reinforcing bars, and for the simulation of bond-slip phenomenon applying contact elements and node springs. The results obtained in the test here proposed for the steel stress had the same behavior as the results presented in the work of Elwi e Hrudehy (1989) and

of Castro (2013), proving that the interface is working properly and yields consistent results. This work has practical applications for problems involving reinforced concrete structures.

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