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OBJECT ORIENTED IMPLEMENTATION OF REINFORCEMENT AND BOND-SLIP FINITE ELEMENT MODELS FOR NONLINEAR ANALYSIS OF REINFORCED CONCRETE STRUCUTRES

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Abstract. *This paper deals with the development of a finite element system to nonlinear analysis of structures of heterogeneouns quasi-brittle material.In the present,it has been implemented incremental-iterative methods to perform the nonlinear solution and some constitutive models for concrete.Herein,it is presented the results for different implementations of finite element that include the reinforcement bar and bond at the concrete-steel inter- face.The base of the system is a finite element program that use the object-oriented programming paradigms as technique of implementation.It was implemented the discrete, embedded and axis-symmetric models for include reinforcement bar,and the bond-link and contact element for treatment of the bond-slip.For both,reinforcement and bond models, it is possible to use finite elements with several interpolation order.The numerical tests performed are presented in order to validate the various models and the several elements implemented.*

1 INTRODUCTION

The finite element method is a powerful tool to be used in analysis of reinforced concrete structures. Permits consideration of members which are nonhomogeneous, defined by irregular boundaries and arbitrarily supported and loaded. Progressive cracking, tension stiffening, nonlinear multi-axial material properties, bond at the concrete-steel interface and other effects can be modelled rationally.

This paper presents a computational system that has for base a finite element program that use the object-oriented programming paradigms as technique of implementation [13]. In the present, it has been implemented incremental-iterative methods to perform the linear or non-linear solution and some constitutive models for material characterization.

This work refers, specifically, to the implementation of the reinforcement and bond-slip models. In order to include the reinforcement bars, it was introduced the discrete, embedded and axis-symmetric point reinforcement models. To treatment of the bond between materials, it was implemented the bond-link and contact models. For both, reinforcement and bond models, finite elements with several interpolation order can be used.

In the numerical analysis performed, the materials were conceived as linear elastic, with the purpose of validate the several models and the various finite elements implemented.

At this time, tests are been performed to check the accuracy of the system, when the materials are modelled with non-linear constitutive models. The concrete has been modelled with scalar damage and microplane models, the steel as elastoplastic material and the steel-concrete interface with different bond stress-slip relations.

2 REINFORCEMENT FINITE ELEMENTS MODELS

In finite element modelling of reinforced concrete structures, there are at least, three distinct alternative representations of the reinforcement: distributed, embedded and discrete reinforcement models. The distributed model isn't widely used and, therefore, it isn't include into the system discussed here.

2.1 Discrete Reinforcement Models

The discrete representation of reinforcement use one-dimensional elements, corresponding to beam or truss elements that is easily superimposed on two or three-dimensional finite element mesh used to represent the concrete.

A significant advantage of discrete representation, in addition to its simplicity, is that it can account for possible displacement of the reinforcement with respect to the surrounding concrete.

The methods to include the bond effects are, usually, related with this representation, and the bond-link or contact elements can be used to connect the steel and concrete nodes, in order to considerate this effect.

One-dimensional finite elements with several interpolation order were introduced into the computational system (figure 1). The bond lost is treated with these elements, through of the introduction of the bond-link or contact elements, treated in the sections 3.1 and 3.2, respectively.

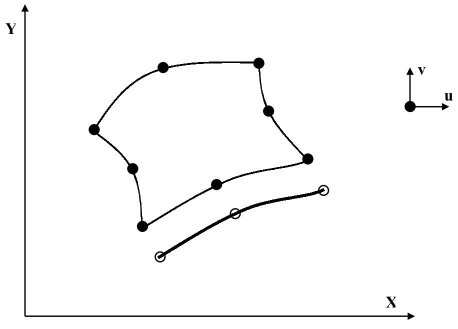

Figure 1: Discrete reinforcement model

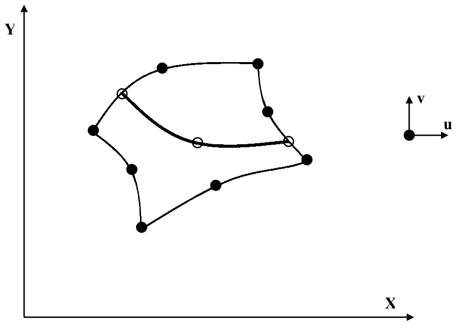

Figure 2: Embedded reinforcement model

2.2 Embedded Reinforcement Models

In the embedded representation, the reinforcing bar is considered as axial member built into the concrete element such that its displacements are consistent with those of the parent element.

One of the formulations of this model suppose that the one-dimensional embedded bar into the parent element keep the perfect bond and its position is such that is coincident to local coordinates system of parent element [6].

Some works have attempt to remove this limitation. In the work of Balakrishna and Murray [2] the bond-slip was taken into account by introducing extra nodes along the bar, in which the characteristics of bond is defined.

Allwood and Bajarwan [1] propose another formulation, in which the bar orientation is generic and the bond-slip could be treated.

Another researchers [12] have preferred to introduce artificial nodes along the steel bar and performing a condensation to remove the additional degrees of freedom in a such way that the bond effects become related with the degrees of freedom of the concrete elements.

The embedded reinforcement element implemented was the proposed by Elwi and Hrudey [5]. In this element, a generic curved bar is built into concrete element (figure 2) in a such way that its geometry is describe with respect to parent element coordinate system. The behavior of reinforcement layer is defined using the degrees of freedom and the interpolation functions of the concrete element, together a appropriated constitutive relation. The bond-slip is take into account introducing additional degrees of freedom, to define the interpolation functions of the curved element and a appropriated bond stress-slip relation.

2.3 Axis-Symmetric Point Element

The axis-symmetric point element is another important element incorporated in the system (figure 3). It can be classified as a discrete element because it is introduced directly in the node of the finite element mesh. It was used the work of Liu and Foster [8] to incorporate this element into the system. This element is fundamental to represent the circular stirrups in concrete structures with circular section and to simulate the phenomenons of concrete confining and stirrups rupture.

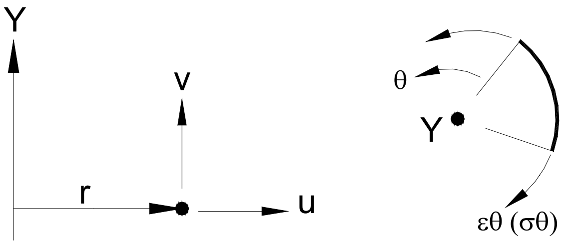

Figure 3: Axis-symmetric point finite element

3 FINITE ELEMENT MODELS TO BOND

When the discrete finite element models are used to represent the reinforcement, it's necessary to add specific elements for treatment of the bond lost. So, bond-link and contact elements were implemented into the system.

3.1 Bond-link Element

This element can be conceived as two orthogonal springs that connects the concrete nodes to steel nodes (figure 4). For each spring an appropriate stress-strain relation is defined.

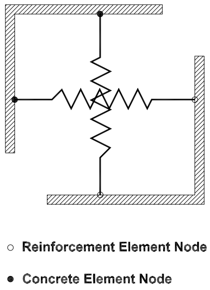

Figure 4: Discrete reinforcement model

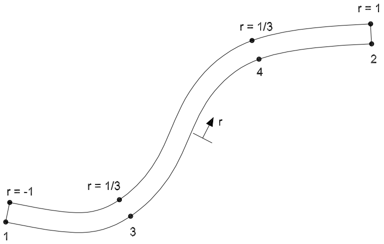

Figure 5: Embedded reinforcement model

3.2 Contact Element

The figure 5 shows the contact element implemented into the system from model proposed by Mehlhorn and Keuser [9]. Different interpolation orders are used to simulate a continuo one-dimensional behavior of the bond lost in the interface between materials.

3.3 Bond Stress-Strain Relations

The behavior of the concrete-steel interface for the bond-link and contact elements, used in discrete models, and for embedded element, must be described from appropriate stress-strain laws. The constitutive relations introduced into the system were the proposed by Doerr [3], Eligehausen, Popov and Bertero [4], Saenz [14], Nilson [10] and Homayoun and Mitchell [7].

4 IMPLEMENTATION OF THE MODELS

The computational implementation of the proposed models was carry out using the object-oriented programming paradigms. It was utilized the FEMOOP ("Finite Element Method Object Oriented Program"), a finite element program that was initially developed at Civil Engineering Department of the Pontifical Catholic University of Rio de Janeiro (Puc-Rio) and have been used in several researches in various brazilian universities. The figure 6 shows, in resume, the super classes of Femoop [13].

The definition of problem type is under `Driver` class (mechanic, heat transfer, etc.), it starts the objects of the `FEM` and `PATH` classes. The solution of the linear or non-linear problems is given by `Path` class, through the appropriate algorithms (incremental loads, displacements, etc.). `FEM` class accomplishes the discretization of the dominium in finite elements, assembles the stiffness matrix and prints results. `AnalysisModel` class manages the kind of analysis performed (plane stress, plane strain, axis-symmetric, solid, etc.). The `Material` class manages material properties. The `Node` class has methods to numbering all degrees of freedom and manages the whole nodal values, such as displacements, loads, support, coordinates. The connectivity and shape functions of the elements is under `Shape` class. The `LoadElement` class calculates the equivalent nodal loads, using the methods from `Shape` and `Gauss` classes. The Gauss points coordinates and their weight to performed numerical integration is given by `Gauss` class, that responses for constitutive state of material in these points. The constitutive relations is built up and actualized by `ConstModel` class.

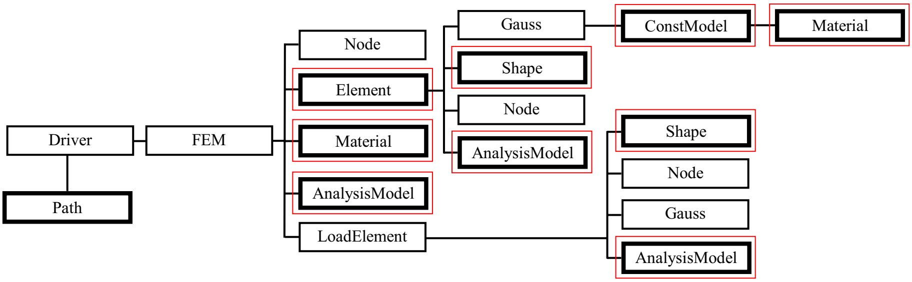

Figure 6: Instances of FEMOOP Classes

In order to implement the reinforcement and bond models, the `Element`, `AnalysisModel` and `Shape` classes were expanded.

Table 1 resumes the subclasses of the `Element`, `AnalysisModel` and `Shape` classes that were utilized in the expansion of the system to include the discrete, embedded and axis-symmetric point reinforcement models and bond-link and contact bond models.

All elements implemented (table 1) has a isoparametric formulation, already existing into the system. However, the embedded model was implemented as a combination of three isoparametric elements: plane (for concrete), bar (for steel) and contact (for bond). Because this, it was necessary to create the derived class `ElcParamEmbed`.

The expansion of the `AnalysisModel` class (table 1) involves the creation of the `PlaneTruss` classes (used in discrete and embedded reinforcement model), `UnidimContact` (used by bond-link and contact model), `UnidimEmbContact` (used in the embedded reinforcement bond model) and `AxisymPoint` (used by axis-symmetric point model). The `UnidimEmbContact` was created because the difference between the embedded reinforcement model and contact model formulations.

The connectivity of the finite elements is under `Shape` class and as each of the rein-

Table 1: Subclasses created for inclusion of the reinforcement and bond models

Model	`Element` class	`AnalysisModel` class	`Shape` class

Discrete Reinforcement	`ElcParam`	`PlaneTruss`	`ShapeLine2`
			`ShapeLine3`
			`ShapeLine4`

Embedded Reinforcement	`ElcParamEmbed`	`Plane` (concrete)
		`PlaneTruss` (steel)
		`UnidimEmbContact` (bond)
			`ShapeEmbLine2`
			`ShapeEmbLine3`
			`ShapeEmbLine4`

Axis-symmetric Point	`ElcParam`	`AxisymetricPoint`	`ShapePoint`
Bond-Link	`ElcParam`	`UnidimContact`	`ShapeContactC2`

Contact	`ElcParam`	`UnidimContact`	`ShapeContactC4`
			`ShapeContactC6`
			`ShapeContactC8`

forcement and bond models has particular characteristics, distinct subclasses were created for each case (table 1).

The `Material` and `ConstModel` classes (figure 6) were also expanded in a such way that the concrete and steel interface behavior was taken into account by different bond stress-slip relations. The figures 7 and 8 show, respectively, the `ConstModel` and `Material` class expansion performed.

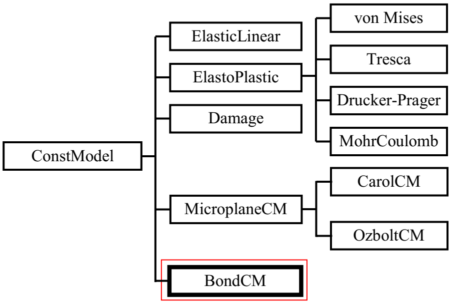

Figure 7: `ConstModel` class expansion

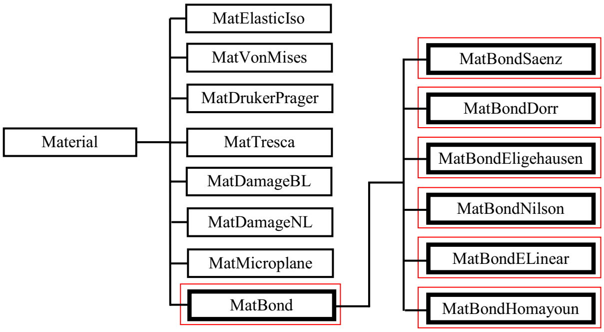

Figure 8: `Material` class expansion

5 NUMERICAL EXAMPLES

In this example, a reinforced concrete ring (figure 9) is modelled using the different reinforcement and bond models introduced into the system.

The materials are supposed linear elastic materials, and the used parameters were such as (figure 9): $A_s/L = 0.025$, $O_s = 0.45$, $E_s/E_c = 8$, $\nu = 0.25$, $E_bL/E_s = 0.27$ and $E_s = 2.1 \times 10^5\ MPa$.

In all discretizations adopted, the mesh is regular. In the first model, embedded reinforcement elements are adopted (figure 10). The mesh is formed by eight quadrilateral elements of eight nodes with one steel layer incorporated, which is described by a four nodes one-dimensional element. If the bond lost is considered each layer node is associated with degrees of freedom that represents the behavior between the materials. Instead, the four nodes is used to define the reinforcement layer geometry without increase in the number of degrees of freedom.

The second and the third models utilize discrete reinforcement elements. Each one of them adopts the regular mesh showed in figure 11.

In order to have compability between the discrete reinforcement layer and the layer used by embedded models, the mesh was created with sixteen 12-node quadrilateral elements to describe the concrete and eight 4-node one-dimensional elements to representing the reinforcement layers.

In the second model, called discrete reinforcement model with contact elements, the lost of bond is represented by sixteen 8-node contact element. The third model, called discrete reinforcement with bond-link elements, adds fifty two springs at the nodes that connects the steel and concrete elements (figure 11).

The figure 12 shows the stress (generalized as $\sigma.A_s/p.L$) along the steel bar for the embedded reinforcement model. The figure 13 shows the results to discrete reinforcement model with contact elements and the figure 14 shows the results obtained using discrete

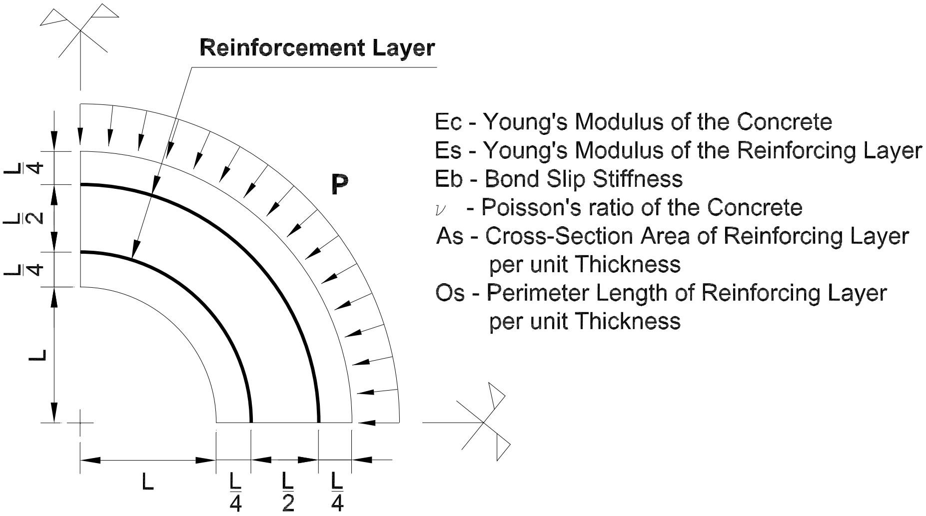

Figure 9: Reinforced concrete ring with two layers of steel

reinforcement model with bond-link elements.

The figures show that the embedded reinforcement model response is best in comparison with the other models in both, perfect and imperfect bond cases.

The figures 12, 13 and 14 also show the number of degrees of freedom and the time spent in the computational processing. They reveal the efficiency of the embedded reinforcement model in comparison to the another models.

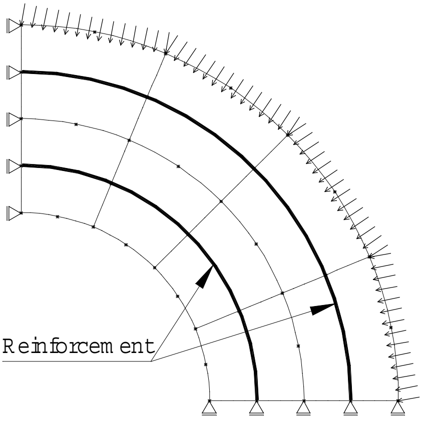

Figure 10: Mesh for embedded reinforcement model

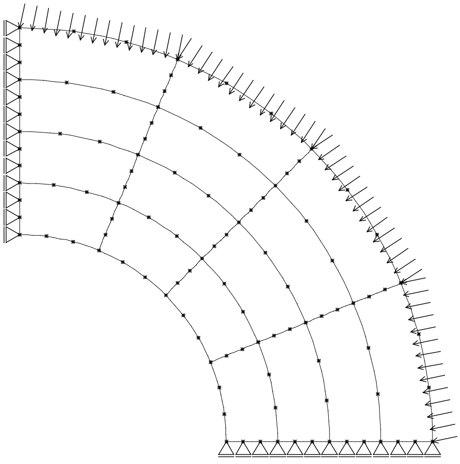

Figure 11: Mesh for discrete reinforcement models

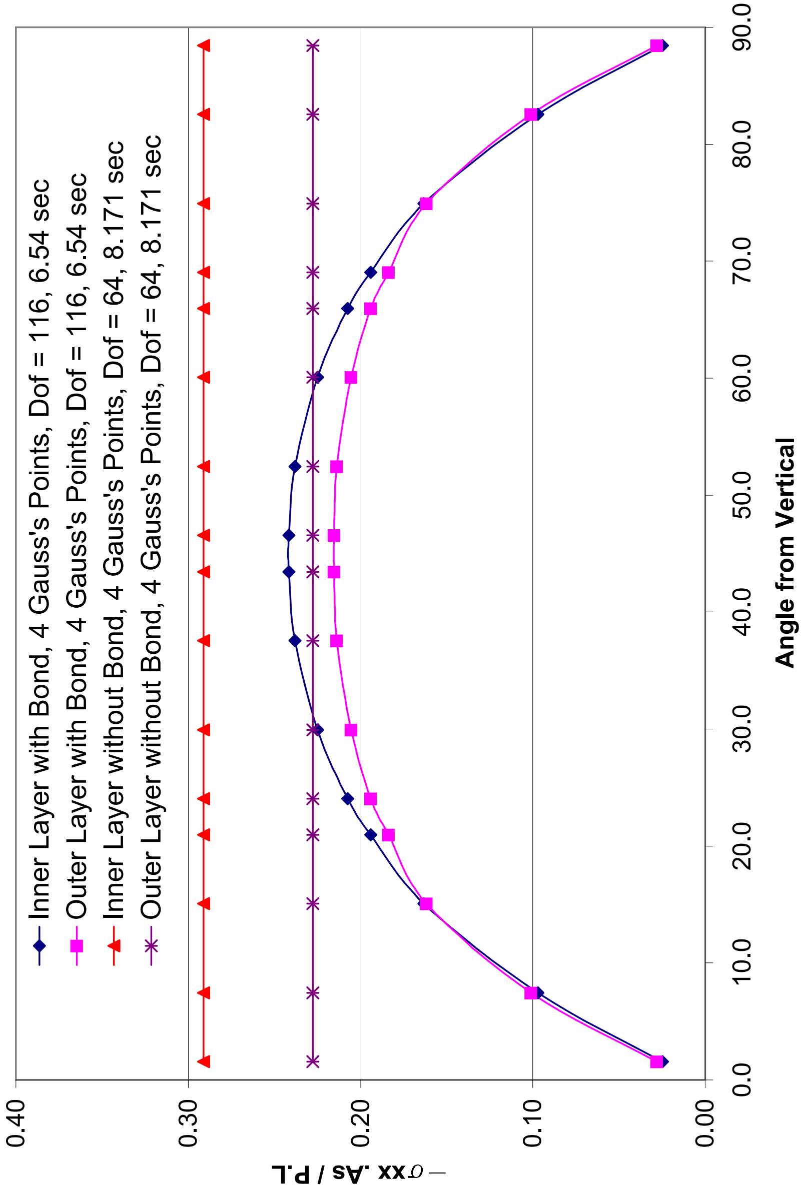

Figure 12: Steel stress to embedded reinforcement model

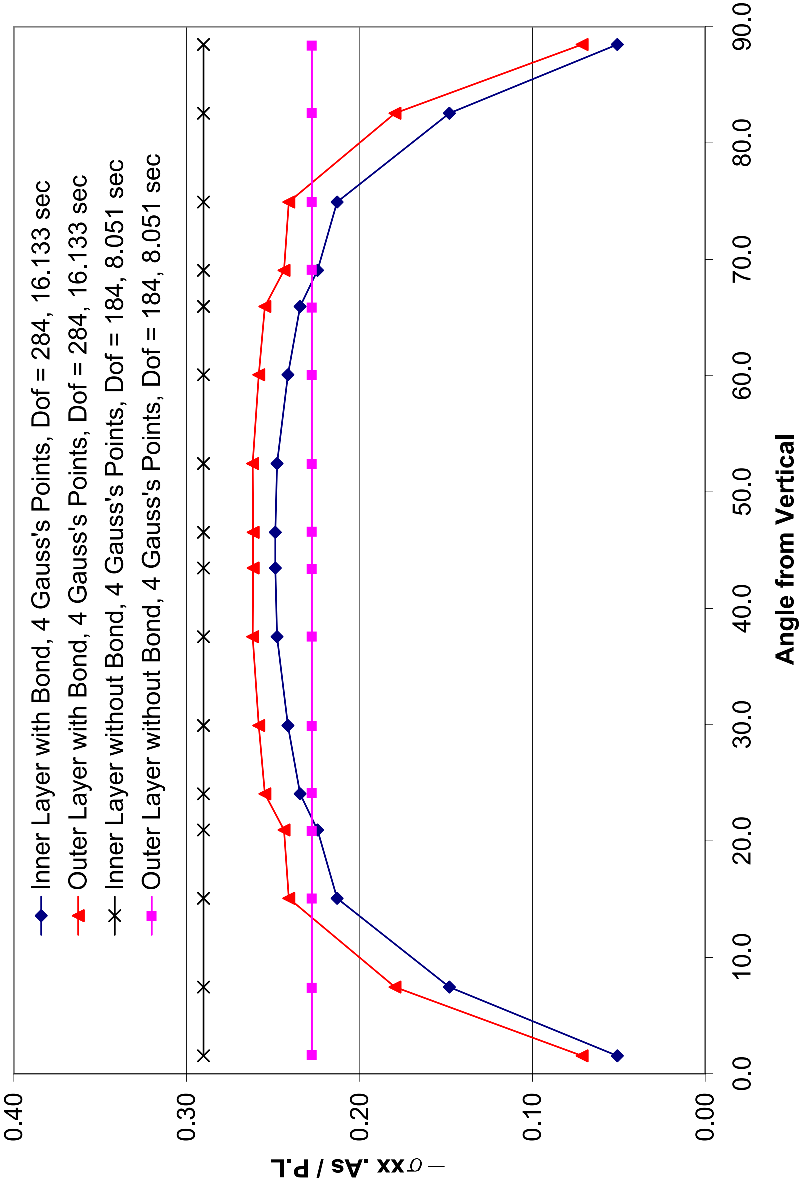

Figure 13: Steel stress to discrete reinforcement model with contact elements

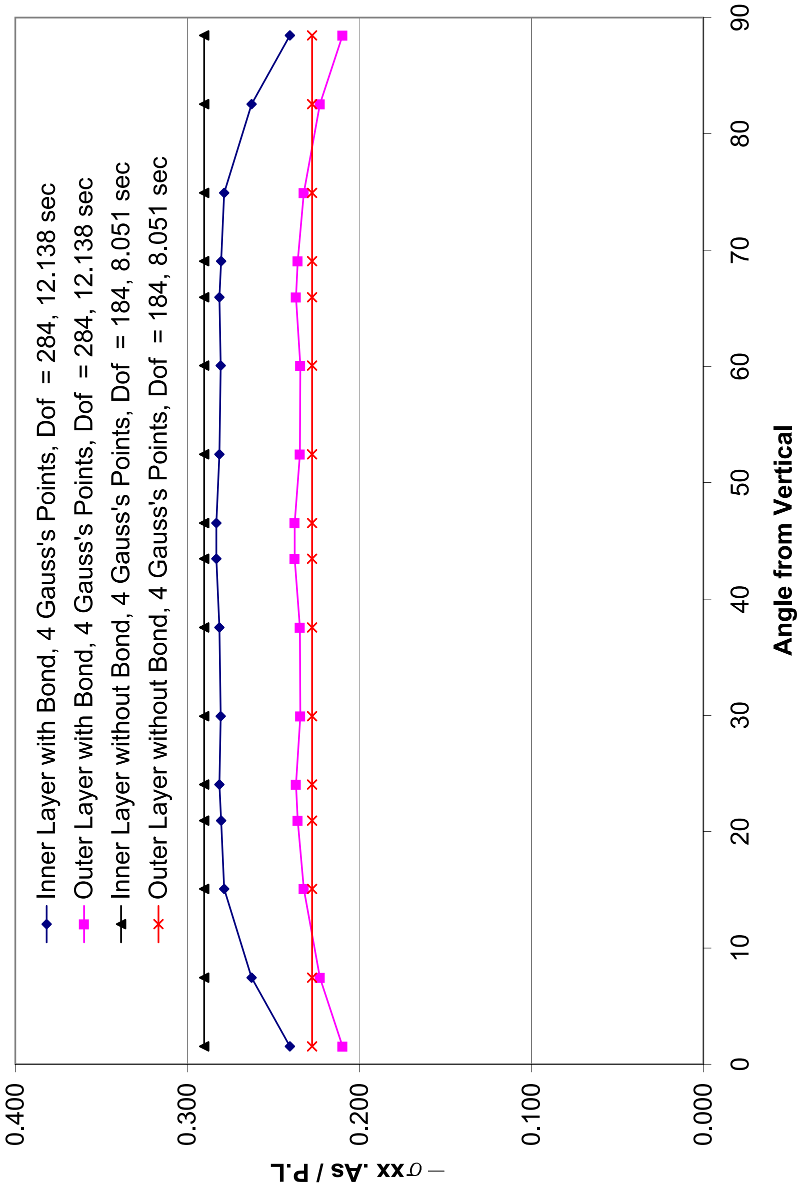

Figure 14: Steel stress to discrete reinforcement model with bond-link elements

6 FINAL REMARKS

The paper presented an ongoing effort in developing a object-oriented computational system that uses the finite element method to modelling reinforced concrete structures, with evidence to the reinforcement and bond models implementation.

The object-oriented programming paradigms allowed the implementation of the proposed models without changes in the basic tools existent into the system.

The numerical examples presented allowed validate the models introduced into the system, particularly the embedded reinforcement model.

The next step in the system development refers to the use of the reinforcement and bond models with non-linear constitutive models to represent concrete behavior: the scalar damage model incorporate into the system with the work of Pitangueira [13] and the microplane model, implemented into the system with the work of Perez and Pitangueira [11].

7 ACKNOWLEDGMENTS

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