Numerical Modelling of the Behavior of Concrete Columns Strengthened by Jacketing

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1. INTRODUCTION

In developed countries, rehabilitation of existing structures surpasses construction of new structures. This has both economic and environmental advantages and is associated with many factors, including safety, serviceability and durability of the structure (Júlio, Branco, & Silva, 2003).

There are several methods for strengthening columns, each one with different advantages, depending on the goals. The present study focuses on structural rehabilitation of columns using reinforced concrete jacketing. This technique is one of the most used in rehabilitation leading to a significant increase of strength and ductility. These are important aspects when a horizontal displacement is imposed. The aim of this study was to quantify the influence of some parameters on the behavior of columns strengthened by concrete jacketing.

The methodology consisted initially in the numerical modeling of a set of laboratory tests conducted as part of a PhD thesis (Júlio E. N., 2001) on the influence of the interface on the behavior of columns strengthened by concrete jacketing. It was intended to simulate slow monotonic tests to which columns were submitted, using a commercial software (Abaqus, 2011) based on the finite element method. Furthermore, parametric studies were conducted, after the validation of the numerical model. These studies considered different values for the added concrete strength, the friction coefficient, and the shrinkage of the added concrete. First, it was found that the strength of the strengthened element increases by considering adherence at the interface, i.e. higher values of the friction coefficient. However, it was also found that increasing the strength of the new concrete layer has advantages up to a limit value. Furthermore, it was concluded that shrinkage of the jacket does not influence the ultimate strength of the reinforced element.

Finally, the slow cyclic tests performed were also modelled, but it was concluded that these are only possible by adopting appropriate constitutive laws and not those available at Abaqus.

2. CONCRETE COLUMNS STRENGTHENED BY JACKETING

2.1. INTRODUCTION

The structural strengthening of columns with concrete jacketing is characterized by increasing the initial cross section of the element along its length, by adding a new concrete layer surrounding it and in which are inserted the new reinforcement steel bars (Gomes & Appleton, 1997).

With this technique it is observed a significant improvement in flexural strength and stiffness in consequence of the increase of the initial section as well as the addition of longitudinal reinforcement, which leads to a reduction of both displacements and deformations. Additionally, there is an increased compressive strength and an improvement in ductility due to the addition of transverse reinforcement.

The critical aspect of this technique lies on the connection between the new concrete and the old one, so appropriate procedures should be taken to ensure a monolithic behavior (Júlio E. N., 2001). The following parameters are the most important when columns are strengthened by concrete jacketing:

1. Roughness of the interface between the initial column and the added concrete: It depends on the type of treatment adopted for the surface of the original column. Hydrodemolition and sandblasting are the most appropriate techniques to increase the strength of the connection;
2. Strength class of concrete adopted in the jacket: concretes with higher strength are the most suitable for increasing the bond strength;
3. Steel connectors applied between the original column and the jacket: shear strength increases with the number of applied connectors.

2.2. EXPERIMENTAL TESTS

It is important to describe briefly the experimental tests carried out by (Júlio E. N., 2001), since these were used to validate the finite element models built in the scope of the present study. A total of 14 specimens were produced, 7 of them were subjected to monotonic load and the rest of them to cyclic load. All the models were also subjected to an axial force to simulate the permanent loads already applied to the structure before strengthening. Table 1 shows the description of each one of the seven specimens tested and subjected to monotonic loading.

Table 1 – Description of the models subjected to monotonic loading

Model	Description of the model
M1G1	Unstrengthened model
M2G1	Model with non-adherent jacket
M3G1	Model with monolithic jacket
M4G1	Model strengthened without interface treatment
M5G1	Model strengthened after sandblasting
M6G1	Model strengthened after sandblasting and with steel connectors
M1G3	Model strengthened with axial force after sandblasting

In this monotonic experiments, for each specimen, a lot of information was collected such as yield load, maximum load and ultimate load. For the numerical calibration of the monotonic tests it was only relevant the load *versus* applied horizontal displacement curves of models M1G1 (Figure 1) and M3G1 (Figure 2).

Figure 1 - Horizontal load vs applied displacement curves of Model M1G1

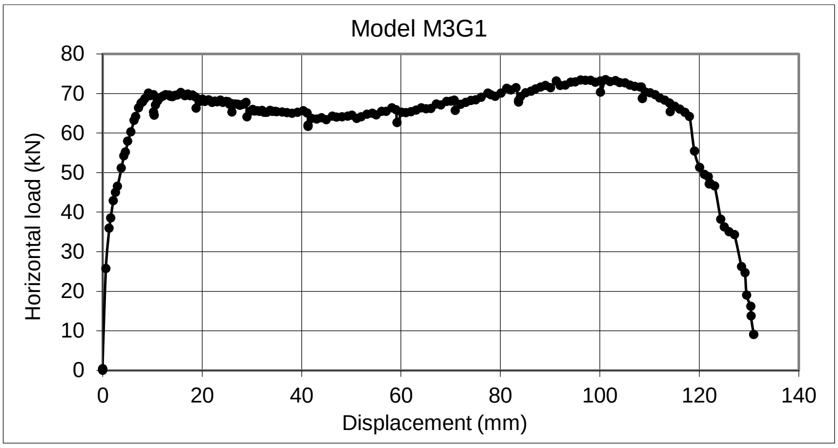


Figure 2 - Horizontal load vs applied displacement curves of Model M3G1

Table 2 shows the description of the specimens subjected to cyclic loadings. To define the imposed displacements history it was determined, for each one of the models, the value of the yielding displacement, δy, obtained from the results of the analogous monotonic models. Four cycles of increasing amplitude equal to 0,25 δy, 0,5 δy, 0,75 δy and δy have been defined and then three cycles also of increasing amplitude, equal to 2 δy, 4 δy, 6 δy and 8 δy have been considered. For the numerical calibration of the cyclic tests, only the hysteretic diagram load *versus* displacement of the model M1G2 has been used (Figure 3).

Table 2 – Description of the models subjected to cyclic loading

Model	Description of the model
M1G2	Unstrengthened model
M2G2	Model with non-adherent jacket
M3G2	Model with monolithic jacket
M4G2	Model strengthened without interface treatment
M5G2	Model strengthened after sandblasting
M6G2	Model strengthened after sandblasting and with steel connectors
M2G3	Model strengthened with axial force after sandblasting

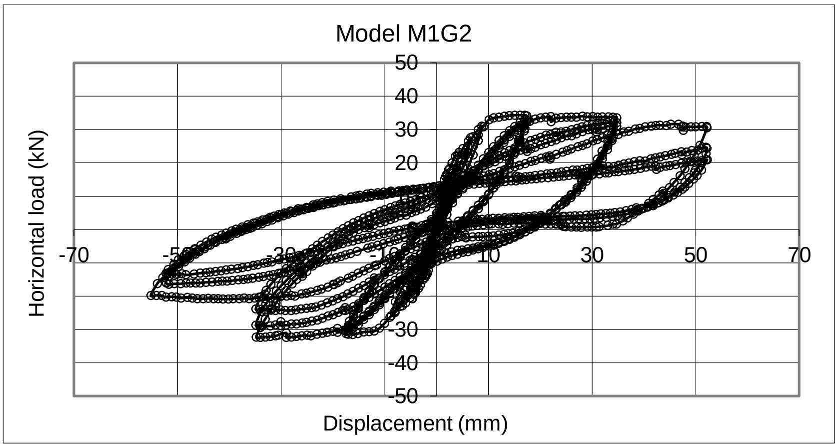


Figure 3 – Hysteretic diagrams load vs applied displacement of Model M1G2

At this point, some important conclusions were taken from these tests:

1) All reinforced column specimens showed a monolithic behavior, regardless of which type of interface treatment was used, except for models with non-stick strengthening;

2) It was not possible to get the pretended non-stick strengthening in models M2G1 and M2G2;

3) Strengthening of the column after or before the application of the axial load is indifferent;

4) The capacity load of the jacketed models is far larger than the non-reinforced models;

5) The relationship between the value of maximum force computed from the results of monotonic tests and the corresponding value obtained from the results of the cyclic tests presents an almost perfect agreement, with the exception of M5G1 and M5G2 models.

3. NUMERICAL MODELLING AND VALIDATION OF RESULTS

In this section, the construction of the numerical models is described, in particular the definition of the geometry for the initial column and for the new layer, the characterization of the constitutive law for the structural materials, the type of finite elements considered and the load applied to the model.

3.1. DEFINITION OF NUMERICAL MODELS

3.1.1. GEOMETRY

Table 3 shows the assumed dimensions for the models and Figure 4 represents the cross section of the reinforced column by jacketing.

Table 3 – Assumed cross-section dimensions for the numerical models

Cross-section characteristics	
Initial columns	0,20 x 0,20 m2
Initial longitudinal rebar	3 Φ 10/ face
Initial transverse rebar	Φ 6 // 0,15 m
Recoating from the model to the transverse layer	0,02 m
Thickness of the additional layer	0,035 m
Additional longitudinal rebar	3 Φ 10/face
Additional transverse rebar	Φ 6 // 0,075 m
Recoating from the reinforcement to the transverse layer	0,01 m

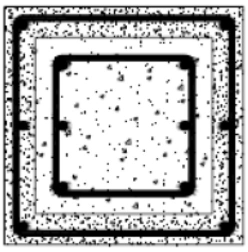


Figure 4 – Cross-section dimensions of a column reinforced by concrete jacketing

3.1.2. MATERIALS

The following material´s constitutive laws were used in Abaqus to simulate the behavior of concrete:

1) Isotropic Linear Elastic Material – to test the geometry and the bond between concrete elements and between the concrete column and the rebars;

2) Concrete Damaged Plasticity – this model considered a physically non-linear behavior for concrete and it is appropriate to simulate the concrete used in the experimental tests;

For the steel elements, a bilinear elastic-plastic material was considered.

3.1.3. BOUNDARY CONDITIONS AND APPLIED LOAD

In the developed models, to simulate accurately the laboratorial tests, the column is rigidly connected to a support base element with large dimensions which bottom surface has all degrees of freedom restrained. The definition of contact between the elements prevents the existence of relative displacements between the surfaces in contact, even if the nodes at the interface of the two elements are not coincident. For the connection of the initial rebar and the respective concrete elements it was adopted the contact type *embedded region*, which allow to incorporate the rebars within the volume occupied by the concrete pieces.

In these tests, a displacement was applied in the initial column 1 m from the top surface of the support base by the imposition of a variation in temperature applied to a rod that is attached at one end to the column and end-fixed at the other end.

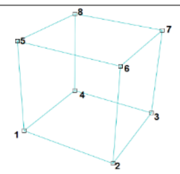
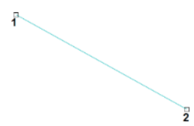
It was also applied a pressure of 4250 kPa on the top surface of the column to simulate the axial force of 170 kN.

3.1.4. MODEL MESH AND TYPE OF ANALYSIS

For the developed models, two types of finite elements were considered. To discretize the original column, the support base and the strengthening layer were modeled considering hexaedric finite elements with 8 nodes. To discretize the rebars 2 node bar elements were used. Each node has three degrees of freedom corresponding to the displacements in the directions of the coordinate axes. In Table 4, it is illustrated the number of finite elements generated in the reinforced model for the mesh assumed.

It was considered an incremental static analysis that allows the user to control the value of the displacement applied.

Table 4 – Finite elements generated for each part of the numerical model

Part	Number of Elements	Number of nodes	Type of finite element
Column	1476	2058	
Base element	45	96	
Reinforced layer	2592	4070	
Longitudinal rebar	74	75	
Transverse rebar	24	24	
Longitudinal reinforcement	56	57	
Transverse reinforcement	24	24	

3.2. MONOTONIC TESTS – DEVELOPMENT AND VALIDATION

Firstly, it was simulated the results of the numerical model for the non-reinforced column with the Isotropic linear elastic material for both concrete and steel. The purpose of this model is to calibrate the initial properties of the materials, to check the imposed displacement and axial force and to see if the generated mesh is appropriated. As observed in Figure 5, the elastic linear concrete model's curve is tangent to the M1G1´s curve. So it can be concluded that the initial properties for concrete were correctly defined and the model is validated.

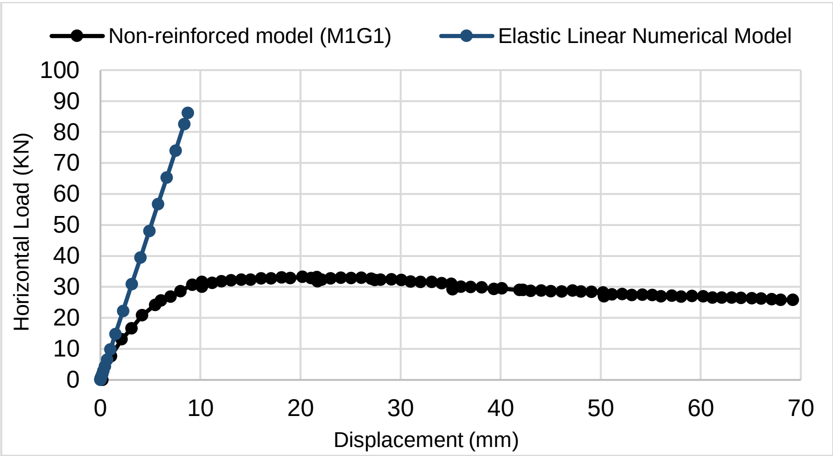


Figure 5- Horizontal Force vs Displacement of M1G1 and non-reinforced linear numerical model

In Figure 6, by analysing the stress distribution fields, we can observe that tractions appear on the same surface as the applied displacement and that compressions appear on the surface located in front of the applied load, as expected.

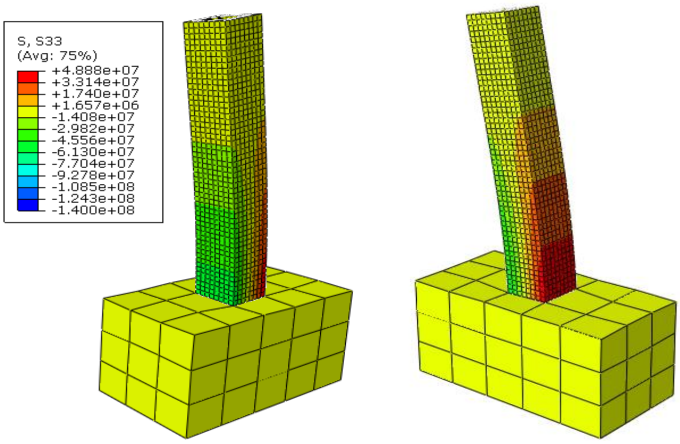


Figure 6 - Stress distribution on concrete of non-reinforced linear numerical model

Next, the non-linear properties were introduced and a positive temperature gradient (about 5000 °C) was applied to a steel rod in order to impose the wanted displacement. With this solution, the laboratory tests are accurately simulated. Figure 7 shows the good agreement between the numerical and the experimental M1G1 results.

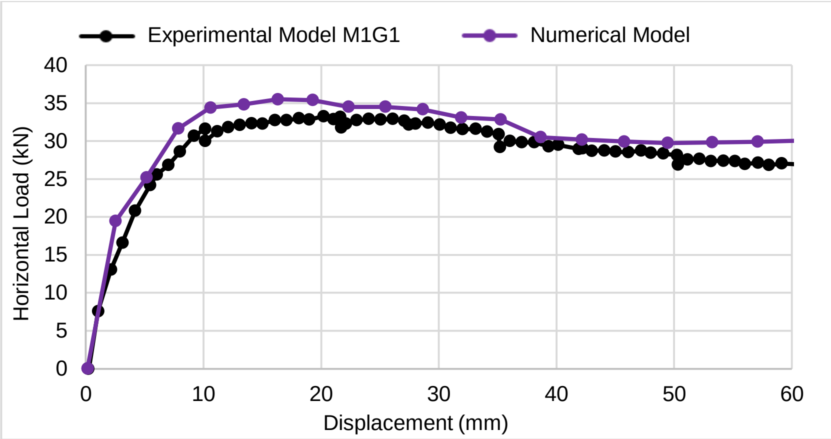


Figure 7 - Horizontal Force vs Displacement of M1G1 and the non-reinforced non-linear numerical model

With the validation of non-linear material properties, modeling of the jacketing of the column with the new reinforced concrete layer was performed. An incremental static analysis was performed, this time by imposing a temperature gradient of 8500 °C, which introduced an axial deformation at the rod of about 130 mm. Figure 8 shows the diagrams load versus horizontal displacement for the reinforced numerical model and for the experimental model M1G3.

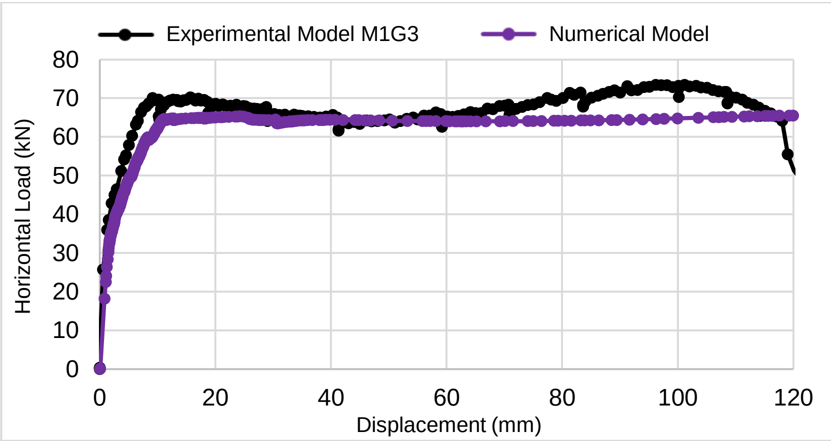


Figure 8- Horizontal Force vs Displacement of M3G1 and reinforced numerical model

The observed results are satisfactory, even if the numerical values are always lower than the experimental ones and the numerical curve only track the behavior of the experimental curve to about 40 mm, since after this value the numerical curve remains almost constant. Figure 9 shows the normal longitudinal stress distributions in the steel (right) and in the concrete (left).

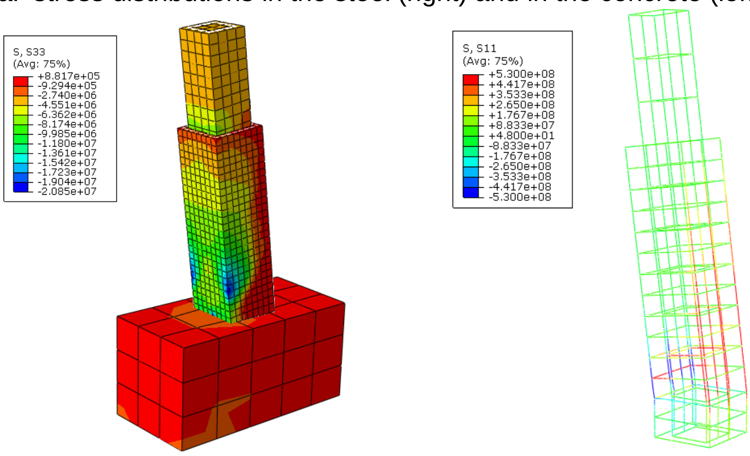


Figure 9 - Stress distribution on steel rebar (right) and on concrete (left) of reinforced jacketed numerical model

4. PARAMETRIC STUDIES

The main goal of this thesis was to conduct a series of parametric studies by changing some parameters of the validated reinforced jacketed numerical model.

4.1. INTERFACE STRENGTH BETWEEN THE COLUMN AND THE NEW CONCRETE LAYER

To study the interface surface, in order to simulate the contact between the original column and the jacket, it is intended to model two extreme situations: the case of perfect adherence and the case of non-adherence. For the first simulation it was used the "rough" option witch does not allow slip to occur between contact points (friction coefficient with infinite value). For the situation of non-adherence, it was used the option "frictionless" witch admits a zero coefficient of friction and so the relative displacement between the two surfaces in the tangential direction is free. In Figure 10, we can see that the non-adherent model is less resistant than the model with perfect adherence, since the reinforcement can slip relative to the original columns and the element does not work as a whole.

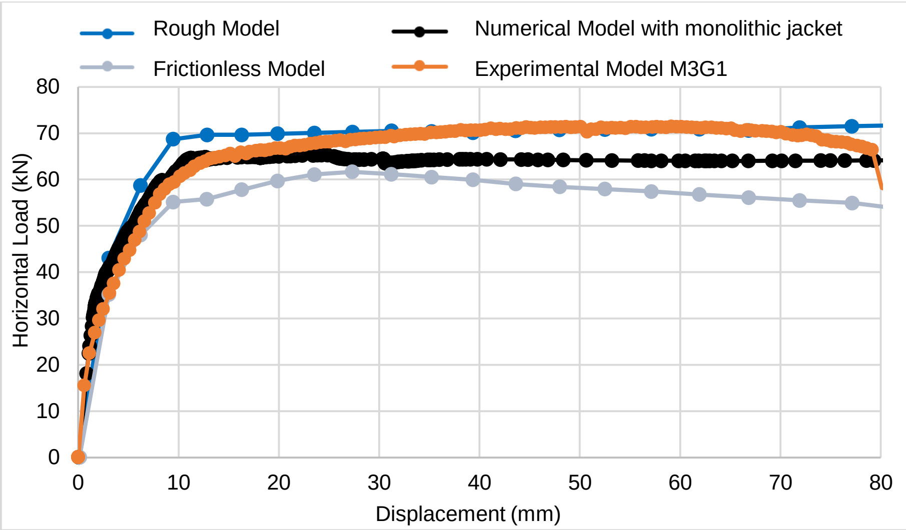


Figure 10 - Diagrams horizontal load vs imposed displacement obtained for the numerical model with monolithic jacket and for the experimental model M3G1 assuming interface elements

4.2. INFLUENCE OF CONCRETE STRENGTH OF THE ADDITIONAL CONCRETE LAYER

To study the influence of the concrete class of the additional layer, the new models used concrete with higher strengths, more precisely 50 MPa and 80 MPa.

Analyzing the results shown in Figure 11 it was observed that increasing the strength of the concrete jacket leads to an increase of the global strength of the element, although without a significant influence.

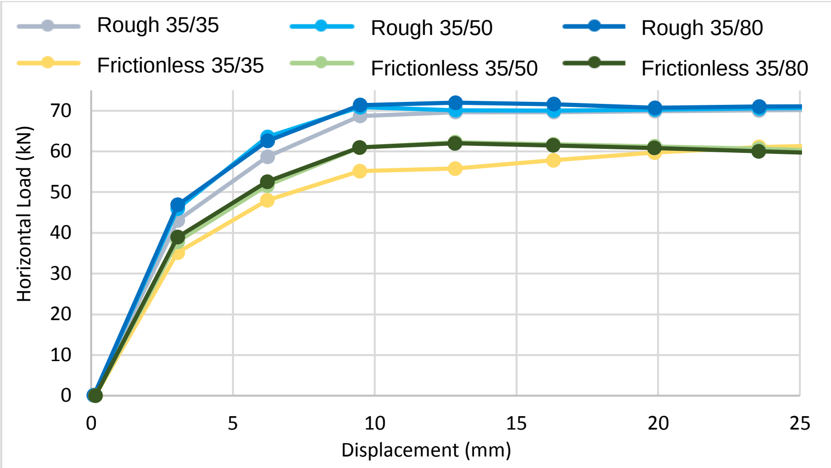


Figure 11 - Diagrams horizontal load vs imposed displacement obtained for the reference models and for the models with higher strengths of the concrete jacket

4.3. COEFFICIENT OF FRICTION

This study aimed to investigate the influence of the friction coefficient considered in the simulation of the behavior of the interface. It was chosen to test the importance of this parameter in the model with a medium compressive strength of 50 MPa. It was observed that the higher the value of the friction coefficient, more resistant the element is. However, it appears that for high values of coefficient of friction, the model has convergence problems, so it was not possible to consider higher values (Figure 12).

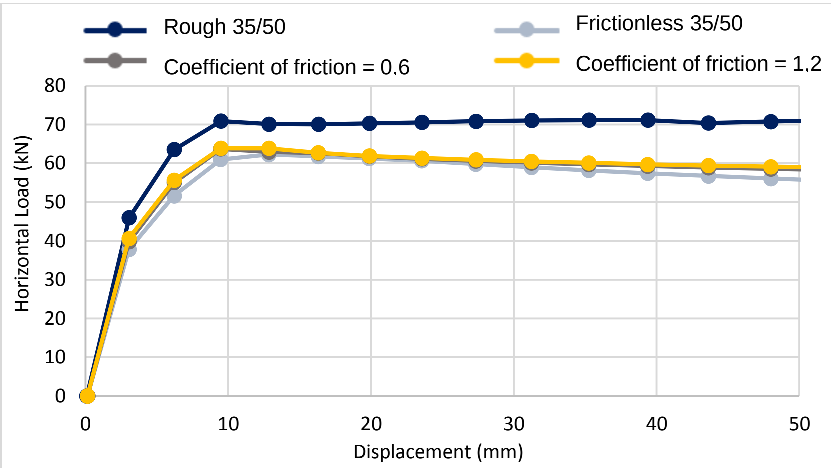


Figure 12 - Diagrams horizontal load vs imposed displacement obtained for the reference models and for the models with different values of friction coefficient

4.4. shrinkage of the new concrete layer

In this subchapter, it is intended to evaluate the influence of shrinkage of the concrete jacket in the behavior of numerical models "rough" and " frictionless ", for the models with compressive strenght of 35 MPa, 50 MPa and 80 MPa. Numerically, the shrinkage can be simulated as the effect of a negative temperature gradient, in this case -30 °C. Overall, observing Figures 13 to 15, there was no significant change in the maximum strength of the reinforced element when the new concrete is subject to shrinkage.

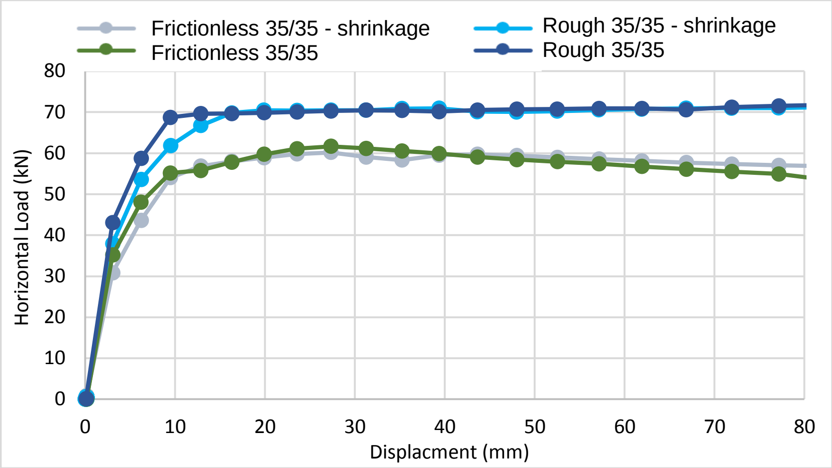


Figure 13 - Diagrams horizontal load vs displacement for the reference models with reinforcing concrete of 35 MPa and the same models subjected to shrinkage

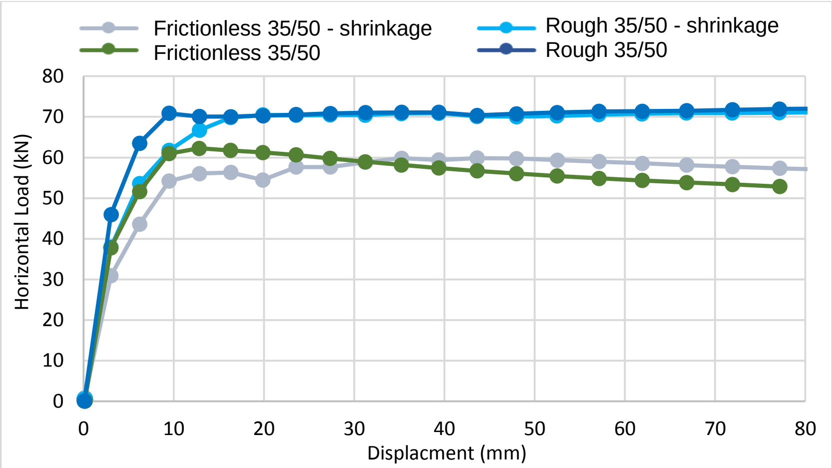


Figure 14 - Diagrams horizontal load vs displacement for the reference models with reinforcing concrete of 50 MPa and the same models subjected to shrinkage

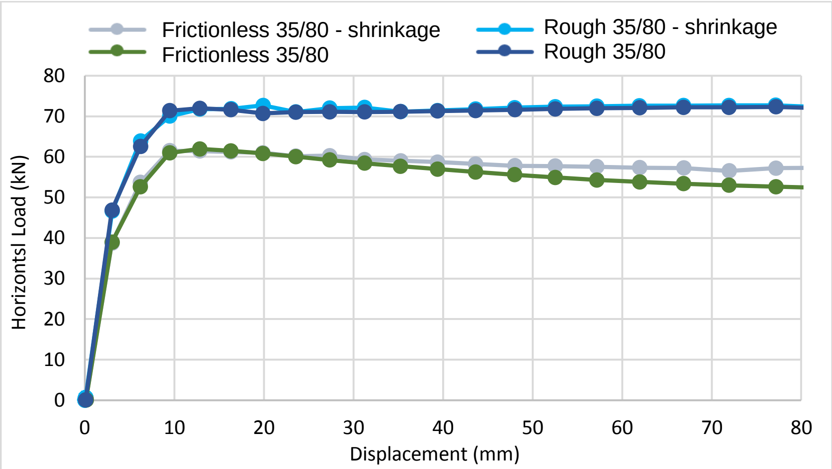


Figure 15 - Diagrams horizontal load vs displacement for the reference models with reinforcing concrete of 80 MPa and the same models subjected to shrinkage

5. CYCLIC TESTS

In a first step, it was assumed for both structural materials a linear elastic behavior. Figure 16 represents the hysteretic diagram force vs horizontal displacement for the numerical linear model and the experimental model M1G2. It was noted that the model behaves as expected in the elastic range, providing a much higher resistance compared to the experimental model that features non-linear behavior.

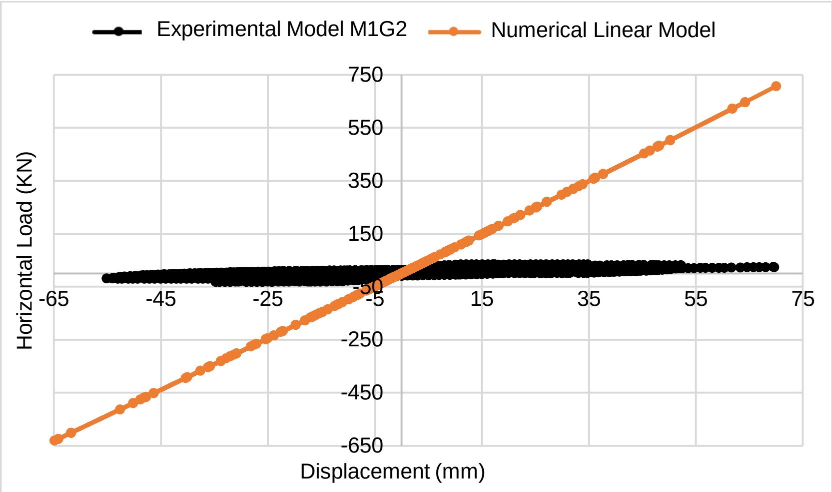


Figure 16 – Hysteretic diagrams horizontal load vs displacement for the numerical linear model and the experimental model M1G2

Then it was considered a non-linear behavior for the materials and the adopted final parameters calibrated for the non-reinforced model under monotonic loading. It is observed, in Figure 17 that there was no degradation of stiffness with the loading progress. This is easily observable taking into account that the slope of the successive branches load/unload are always substantially parallel. The CDP model can not represent the gradual loss of rigidity in the course of loading history, so is unable to adequately simulate the behavior of concrete elements subjected to cyclic loading.

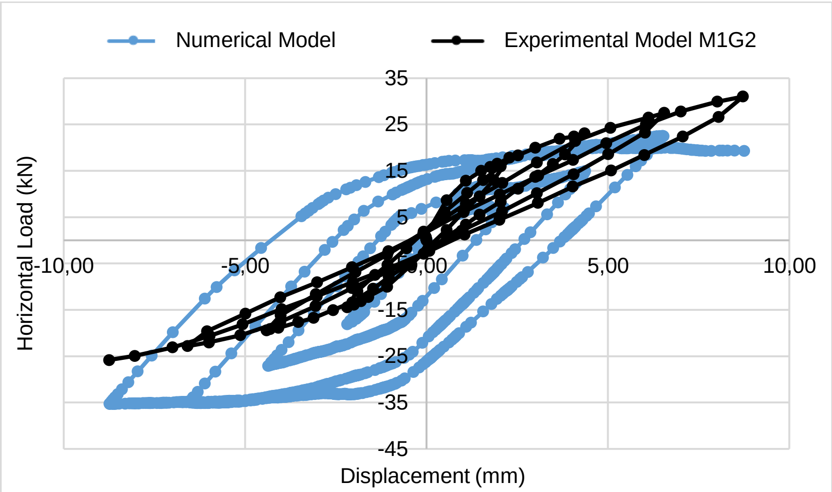


Figure 17 – Hysteretic diagrams horizontal load vs displacement for the non-linear numerical model and the experimental model M1G2

6. CONCLUDING REMARKS

6.1. CONCLUSIONS

The main conclusions that can be drawn from the performed study are the following:

1) CPM can easily simulate reinforced concrete properties for monotonic loading and Abaqus shows a lot of interesting information such as stress distribution in concrete and in steel rebar.
2) The strength of the reinforced element increases with the consideration of adhesion between the interface elements, since the column and reinforcement act as a whole and slipping is prevented, and with higher values of the friction coefficient
3) By increasing the strength of the new concrete, the global strength of the monolithic column slight increases. In fact, for concrete 50 MPa, the model is able to slightly improve the efficiency of jacketing technique, although for high values of average strengh of the concrete this option no longer offers advantages.
4) The consideration of the concrete jacket shrinkage does not lead to an increase of the ultimate strength of the reinforced element.
5) The constitutive models available in Abaqus can not represent the gradual loss of rigidity in the course of loading history and so they are unable to simulate the behavior of concrete elements subjected to cyclic loading. It turned out to be clear that a correct simulation would require the programming of appropriate constitutive relations in the routines that Abaqus allows to be changed by the user.

6.2 FURTHER DEVELOPMENTS

For those who seek to continue the study of numerical modelling of concrete columns strengthening by jacketing developed in this dissertation, the following studies are suggested:

1. Numerical modelling of reinforced concrete columns by jacketing subjected to monotonic loading using the Smeared Crack Concrete Model;
2. Numerical modelling of the interface between different concretes, depending on the type of treatment;
3. Numerical modelling of connectors applied between initial column and additional layer;
4. Development of a subroutine that allows to correctly simulate non-linear behavior of reinforced concrete when subjected to slow cyclic loading.

7. REFERENCES

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