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An educational program for teaching design and detailing of reinforced concrete beams

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Abstract. Reinforced concrete (RC) beam design has been automated for decades, and a large number of different comercial and free softwares have been developed for this task. Nonetheless few simple free tools independent of large general-purpose softwares are available for educational purposes and/or validation of analysis and design of RC beams. This paper presents a simple desktop-based graphic interactive program able to carry out the analysis, design and complete detailing of RC continuous beams for buildings, with several options and configurations for the tailoring of the engineer design preferences. It provides an easy-to-use process which allows a student to develop the sense and the experience on design of RC beams. The graphical user interface (GUI) is inspired by the FTOOL program.

Keywords: reinforced concrete, graphical user interface, beam design.

1 Introduction

The design of reinforced concrete beams is a lengthy process which has been automated in dozens of softwares around the world for decades. Due to the local mandatory use of national design codes, these programs are usually restricted to specific countries. In Brazil, there are many commercial programs which include beam design reflecting the preferences of the developers, the consumers and under the Brazilian Code NBR6118 (Design of Concrete Structures [1]). For educational purposes, however, there are very few options which are self-contained, independent of a large software suite and directly applicable to the design of isolated beams. In practice, while teaching RC design one starts with isolated members. A very interesting tool is the mobile-based application named *ApoioDuplo* [2] available for IOS platform.
With respect to the design of beams under NBR6118 prescriptions, one of the most difficult tasks is the cutoff of flexural reinforcement when various layers of reinforcement are present.
This work describes the development of an educational desktop program for teaching analysis, design and detailing of RC beams under static loads according to the prescriptions of the Brazilian Code NBR6118. The program was written in C++ and the User Interface was built with IUP graphical package. In its present version it is possible to design reinforced concrete beams for the Ultimate Limit State (ULS), verify the Serviceability Limit States (SLS), as well as visualize graphically information about the design process such as cutoff points, diagram of forces, displaced bending moment diagrams.
The author has developed the program during his years as lecturer of the disciplines Reinforced Concrete I and II at UFOP (Universidade Federal de Ouro Preto) and more recently at UFC (Universidade Federal do Ceará). The program has proven to be a valuable tool for showing the students examples of beam design, helping them understand the principles of analysis, design and detailing, and may also be an option for engineers who wish to design isolated beams with simplicity and without the overhead of a large commercial program. It has been nicknamed E-VIGA, inspired by the e-tools programs developed by Prof. Luiz Fernando Martha and others.

2 Interface Layout

Figure 1 displays the main program window with a view of an example of a RC beam with its geometrical and static model, while Figure 2 shows the same beam after complete analysis, design and detailing. These views can be shown together in the main program window switching on the view parameters. Most of the program functionality resides in this main window, and the commands are reflected as main menu items and as buttons on the panel below.

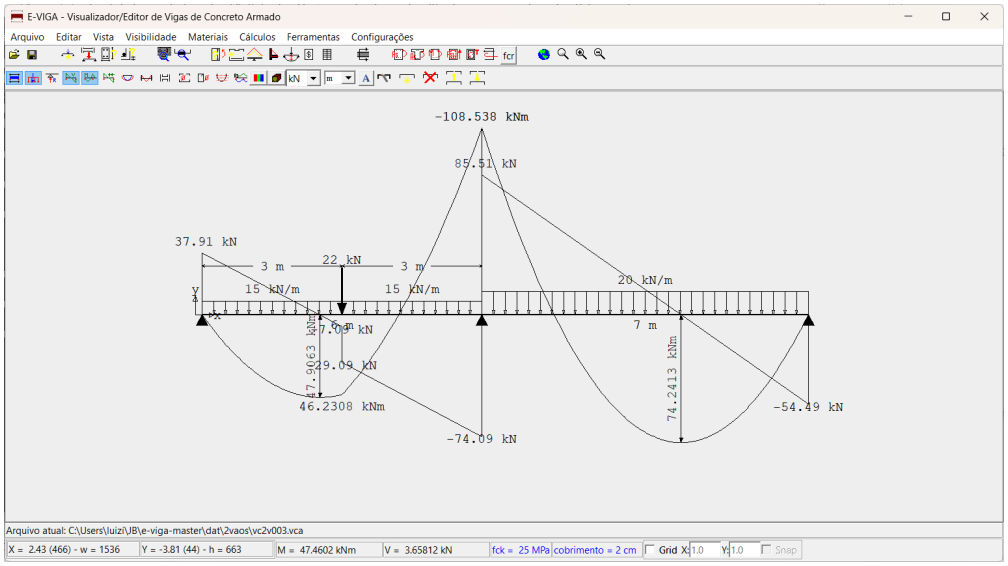


Figure 1. Geometry and loads of continuous beam

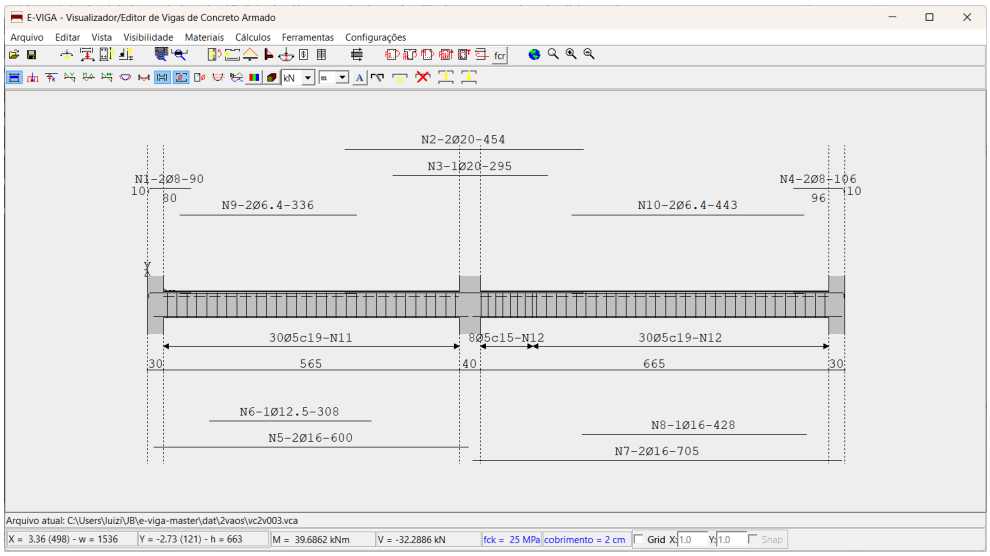


Figure 2. Main window with designed beam

3 Program structure

3.1 Main code for RC beam design

The C++ code architecture is based on two main classes: One (class `cVigaCont`) is responsible for taking care of the structural model and is responsible for the evaluation of section forces and bending moments for every load case in the beam design. In terms of analysis model it contains a simple finite element (FE) solver for beam problems, and several methods to help the detailing of the RC beam (e.g. finding points of specific bending moment

or transverse force). The other main class (class `cVigaCA`) is responsible for the management of the RC beam itself, including material, geometry, longitudinal reinforcement bars, transverse reinforcement bars (stirrups). It contains methods for designing, detailing and verification the beam and is customizable un many aspects as described later.
There are other auxiliar classes, which are contained in the structure of the continuous beam class, such as classes for representing longitudinal reinforcement, transverse reinforcement, materials (concrete and steel) and a special class named NBR6118 which handles several code prescription operations such as minimal and maximum reinforcements, minimum cover, partial coefficients and many other design code related operations.

3.2 Graphical user interface

The GUI package employed in this work is IUP – Portable User Interface (www.tecgraf.puc-rio.br/iup). It offers a simple API in three basic languages: C, Lua and LED. IUP's purpose is to allow a program source code to be compiled in different systems without any modification. Its main advantages are high performance, due to the fact that it uses native interface elements, and fast learning by the user, due to the simplicity of its API. The library contains several basic interface elements and predefined dialogs. Among its characteristics are simplicity, portability, customization, flexibility and extensibility.
The 2D drawing of the elements is done with the CD-Canvas Draw (http://www.tecgraf.puc-rio.br/cd) package developed by the same group and easily embedded into IUP applications. 3D Drawings are carried out using the OpenGL widget from IUP (`IupGLCanvas`).

4 Design sequence of a RC beam

Typically, the sequence of operations for the design of a RC beam, which is mimicked by the program, is carried out in the following sequence:
• Establishment of the static model of the continuous beam. The user enters each theoretical span, the loads for each span (distributed, point loads) and the support conditions (simple, free, fixed or elastic rotation). After this operation the static analysis of the beam is carried out immediately.
• The beam height and width, along with the span lengths, type and dimensions of the supports are defined. The program allows the user to evaluate a prior design for the height of the beam based on the maximum bending moment from the linear analysis. This operation defines completely the geometry of the beam as it is defined in the construction site.
• Design of reinforcement for the critical sections for the bending moments for the load case prescribed by the design code. Assuming proportionality between bending moment and tension reinforcement, carry out the cutoff of bars according to code prescriptions.
• Design of transverse reinforcement in the form of stirrups based on the values of the transverse forces for the critical section and detail of the distribution of stirrups that lead to economic ranges of transverse reinforcement.
• Evaluate the need for constructive reinforcements along the beam length and complete the detailing of the remaining bars, a well as the beam-column connection region with special care to the anchorages.
• Check serviceability limit states (deformation limits and maximum crack widths).
Highlights of some of these steps are presented in the following subsections.

4.1 Bending moment reinforcement calculation

For the critical sections of the bending moment the reinforcement is evaluated using constant distribution of stresses (Whitney block) and strain “domains” as specified by the Brazilian Code. The program then selects the bar diameters and quantities, carrying out the distribution in two or more layers if necessary.
The evaluation of this reinforcement uses the correct position of the centroid of the group of bars to get the lever arm of the resisting moment, therefore an iterative calculation is necessary after choosing the number and diameters of the bars. The user may choose among three schemes for this operation: (a) the program uses an internal table for the selection of bars; (b) the program chooses the “best” bar for the detail (i.e. the one which leads to fewer layers); or (c) the user specifies a default bar which will be used in all the critical sections. This gives the user

flexibility to produce and test different designs according to his personal taste or local construction culture.

4.2 Bar cutoff and splicing

The Brazilian Code NBR6118 establishes that the anchorage of a bar of the flexural reinforcement must start when its tension force begins to reduce, and must be at least the basic anchorage length given by an expression depending on the steel, concrete, bar position and adherence; additionally, it must be 10 diameters after the theoretical point of zero tension (i.e. after the bar is completely anchored), and the linearized tension resisting force (which is zero at the beam end) must envelope the diagram of the tension force demand (the diagrams must not cross). This last requirement is frequently ignored in textbooks on RC design [3] and may be fulfilled in a simplified way by anchoring the bar beginning at the point of theoretical zero tension.
The implementation of these requirements is a difficult task, but it has been successfully implemented in the application, which gives the user the option of this refined cutoff of bars. The last requirement is usually dominant when the tension force diagram becomes very steep. It should be noted that it is common practice to work with the bending moment and not with the tension force, which are assumed to be proportional, as well as amount of reinforcement and bending moment are considered proportional, which is on the safe side.
Some options for bar cutoff and detailing are configurable by the user, who can decide how many bars should be grouped in each point of cutoff, if “floating” bars are allowed and other configuration options.

4.3 Transverse reinforcement

The application designs the transverse reinforcement as closed loop stirrups evaluated with one of the two models allowed by the Brazilian Code, at the choice of the user. The first model uses struts inclined at 45 degrees while the second model leaves to the designer to choose this angle, in a predefined range.
Several options are available for the distribution of the stirrups: uniform distribution, end values distribution and the two recommended ones: (1) detailing for a subdivision of the span (1m, 2m or 5m), and (2) detailing in three zones where the end zones employ the transverse force at the left and right ends of the span, and a middle zone for which the minimum code based transverse reinforcement is already sufficient. This last scheme is usually the best for beams in residential buildings, which usually do not have very long spans.

4.4 Serviceability verification

In traditional RC concrete beam design the dimensions and reinforcements are usually defined with the ULS (Ultimate Limit State) criteria, and the serviceability is analyzed in a second step. For not very slender beams this workflow leads to designs which already satisfy Serviceability Limit States (SLS) requirements. For longer spans, however, beam deformation and cracking may be determinant of the final dimensions and reinforcement. It is difficult to design beams for SLS directly, since there is a complicated relation due to nonlinearity and cracking.
In that sense, the application provides a window for SLS verification for an already designed beam.The two main functionalities of this dialog is the verification of the beam deformation and the crack opening limits.
The evaluation of the short-term beam displacements is carried out using a finite difference scheme where the curvatures are integrated along the beam length to obtain the displacements taking in to account the correct section stiffness which is dependent on the bending moment level. This process can be carried out incrementally, applying load steps to produce better results, accounting for the evolution of cracking and the gradual modification of the section stiffness, in a procedure which resembles the nonlinear grillage strategy which is implemented in some commercial codes.

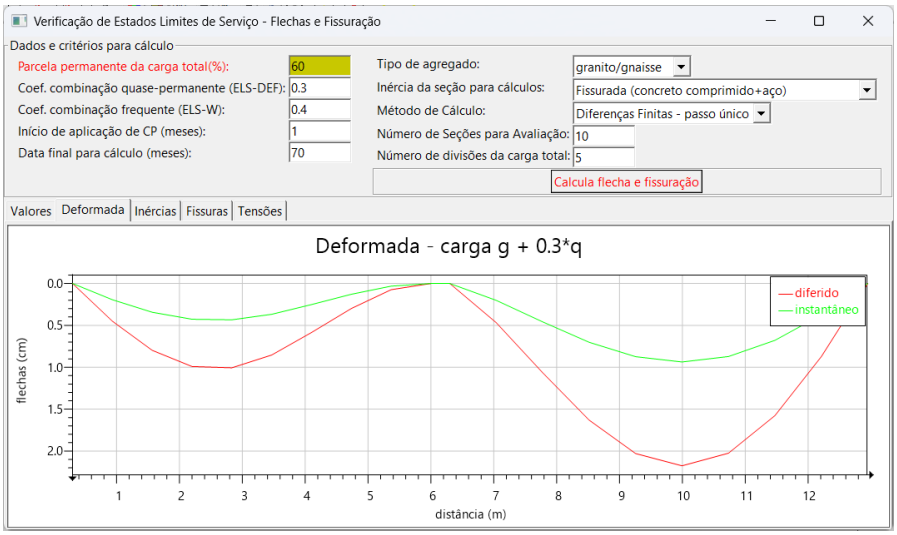


Figure 3 – Beam verification for Serviceability Limit State

5 Additional tools

5.1 Beam interactive edition

The automatic design of beams with very different characteristics may not be fully accomplished with the algorithms developed in the application. Some special cases may be very hard to automate. For these situations, and also for users who have their own preferences for RC detailing, the application includes a basic interactive editor for modification of a current design of the longitudinal reinforcement. It is possible to create new bars, edit existing bars, delete, join or split two separate bars in the same span or in adjacent spans.

5.2 Additional calculators

In order to help the user in typical daily tasks and also the students who wish to check some of the programs design evaluations, a series of calculators are implemented in the “tools” menu of the application. These include design of rectangular and T sections for bending, design of sections for uniaxial bending with normal force, verification of sections for bending moment, evaluation of development and anchorage length.

6 Assessment of calculation results

This section presents the final detailing results obtained by the software and compares to the manual design carried out in the book edited by Kimura et al [4] from IBRACON (Brazilian Concrete Institute) Concrete Design Guide, which is a recommended book by IBRACON and ABECE (Brazilian Association of Consulting Structural Engineers) Of course several design decisions which reflect the authors’ personal preferences are employed in each case so that similar details are expected, with some variations. Figure 4 adapted from [4] displays the final detailing of the beam with emphasis on the flexural reinforcement.

The same geometry, materials and boundary conditions were employed to design a beam with the developed formulation, and the results are depicted in Figure 5. The designs are in fact very similar in terms of flexural reinforcement, including similar cutoff points for the flexural positive and negative reinforcements. The main difference on the positive reinforcement of the second span is due to the use of a T section in the hand calculated beam, and it was noted that the negative bending moment (hyperstatic) on the center support was redistributed from the linear analysis by a factor of 0.9. It seems that the hand calculation did not take into account the limits of neutral axis which NBR6118 prescribes when moment redistribution is employed.

7 Summary and conclusions

A graphical interactive program for the analysis, design and detailing of RC beams was presented in the present paper. The main characteristics of the desktop application were described, like program structure, user interface, beam design options and examples of the program workflow.

This is still work in progress since there are a lot of functionalities which would be interesting to include in the code, such as FE nonlinear analysis, fire design, integration with CAD/BIM models. It would also be interesting to implement new advanced features such as reliability analysis and design optimization. A web-based version would be a major advance, but it would require a time-demanding change in graphical platforms.

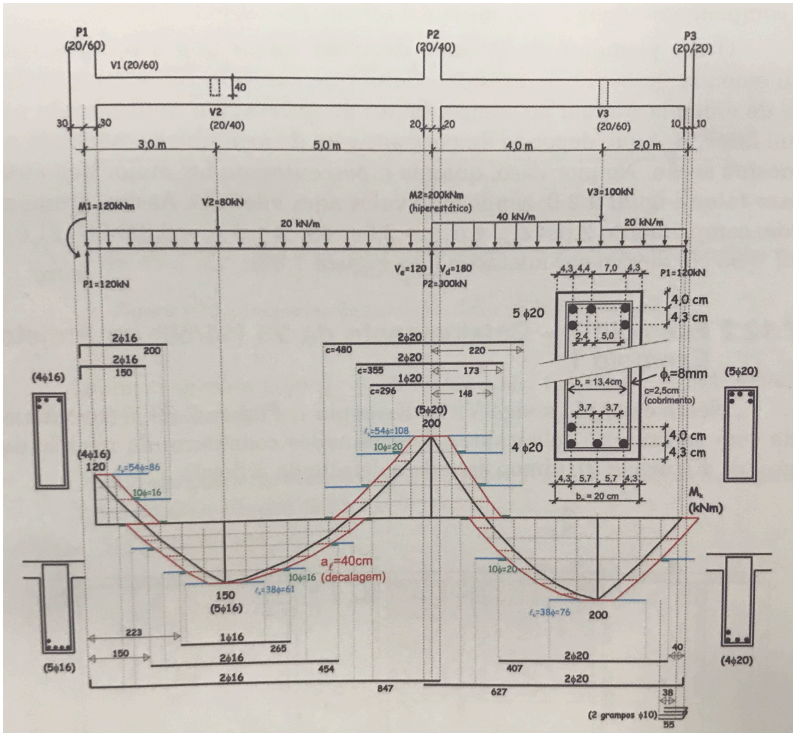


Figure 4 – Example of flexural design of a continuous beam [4]

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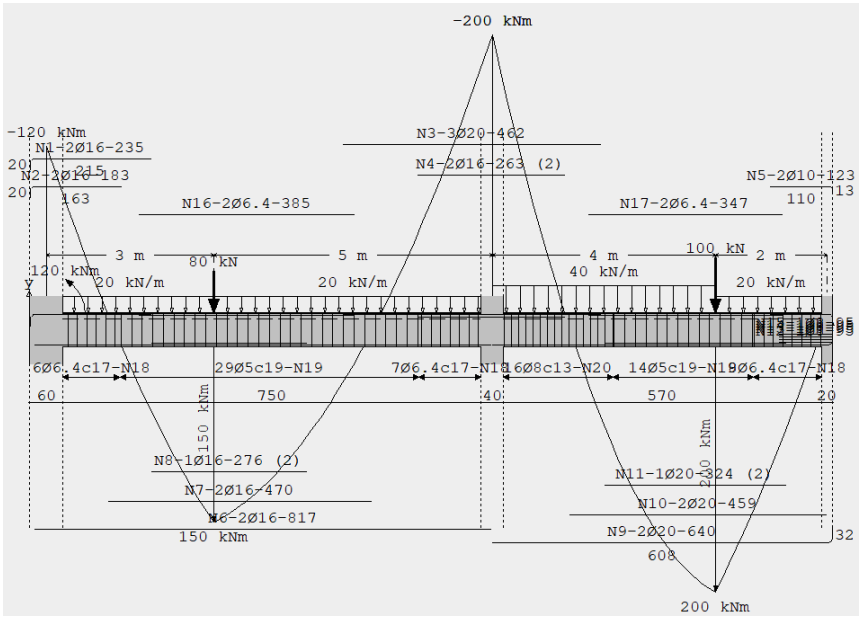


Figure 5 – Beam designed by the application – final detailing

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