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Highlights

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- With the aid of optimization methods, a broader teaching framework could be reached for courses of Reinforced Concrete Design.
- Visual programming with ANSYS SpaceClaim represents a potential tool to aid students of Reinforced Concrete Design courses for better design assessment.
- CALRECOD offers a great learning environment for Reinforced Concrete Design practices in Higher Education as it enhances further learning outcomes in students as well as research.

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Research paper

CALRECOD — A software for Computed Aided Learning of REinforced COncrete structural Design

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ABSTRACT

It is presented the development and implementation of a new computed aided learning MatLab Toolbox for the design of reinforced concrete structures named as CALRECOD for their abbreviation *Computer Aided Learning of Reinforced Concrete Design.* Such development emerges as the result of a series of research works in the Autonomous University of Queretaro with the main purpose of improving the way in which the design of reinforced concrete structures is taught in high education institutions. CALRECOD uses optimization methods and algorithms to aid students in their design interaction learning so that they are able to compare their own designs and what commercial software delivers with optimal ones given certain load conditions on the elements or structures. The software consists almost entirely of MatLab functions (.m files) and the ACI 318-19 code is taken as their main design reference to make it internationally useful, although in some cases the Mexican code NTC-17 specifications are used. Besides MatLab functions, the software consists as well of ANSYS SpaceClaim script functions (.scscript files) as an additional tool for the aid in the visualization of design results in a 3D space in the software ANSYS SpaceClaim. CALRECOD has proven to be versatile, flexible and of easy use with a huge potential to increase learning outcomes for students in high education programs related with the design of reinforced concrete structures as well as to enhance the creation of efficient interactive environments for researchers and academics focused on the development of new design and analysis methods for such structures. With their optimization design functions, a solid comparison platform of designs' performance could be laid out, and with its extended function design packages for structural systems, reinforced concrete design courses could be enhanced in a great deal regarding their program content's scope. The software can be found at: https://github.com/calrecod/CALRECOD.

1. Introduction

The computed aided teaching and learning for Higher Education has become an essential paradigm nowadays for many areas of applied sciences like Engineering, in which it is of great importance to consider as a Professor the best computational tools available for teaching, given that most engineering design processes are almost entirely computerized [1]. At this point and under this such context, there have been developed numerous Computed Aided Learning software and packages in the area of structural mechanics and applied sciences by various Universities and Institutions such as CALFEM *(Computed Aided Learning of the Finite Element Method)*[1] from the University of Lund, Sweden; or MAT-FEM[2] by the CIMNE *(Centro Internacional de Métodos Numéricos de Ingeniería) in the Polytechnic University of Cataluña, Spain.*

In other universities however, there is a tendency by students to adopt specialized commercial software of structural analysis to support their learning of structural mechanic subjects, and only if their university offers fully available student licences of such software, such as SAP 2000, Revit-Robot, ETABS, among others, and even though such software is advantageous to solve problems very quickly, the interaction with what is actually being computed by such software can be very limited for the users and it would be required for them to have a solid knowledge of the software capabilities and functions to use them properly, otherwise there would be the risk for students to fall into misinterpretations of results or to simply provide wrong input data for any problem at hand. On the other hand, specially for undergraduate engineering programs the tendency is most likely

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1 https://www.byggmek.lth.se/english/calfem/
2 https://www.cimne.com/mat-fem/default.asp

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for manual calculations and theoretical aspects, lacking any implementation of technological packages to aid students in their learning process (due mainly to time and curriculum constraints [1]) which goes in contrast to what is required by industry professionals (see [2–4]). Therefore, Computed Aided Learning software represents a great solution approach to counteract over this mentioned limited didactic interaction that is commonly experienced by engineering students learning Computer-Based methods.

It has been demonstrated that using computational simulation practices in engineering education has enormous benefits (see [1]), as it can link theory and the phenomenon understanding to what is actually done in industry for real problems through the combination of disciplinary knowledge and the thought processes involved in formulating such problems and their solutions, so that the solutions are represented in a form that can be effectively carried out by an information-processing agent. This concept has been recognized as *computational thinking* [5] by which practitioners are proficient not only at using tools, but also at creating them and understanding the implications of their capabilities and limitations [6]. Furthermore, it has been demonstrated (see [7–9]) that combining computational thinking with disciplinary learning can serve as an effective medium for deeper insights in math and science, enhancing students' comprehension of complex systems' behaviours and support those predicted from new designs'.

Other educators and researchers in the areas of science, technology, engineering and mathematics (STEM) have proposed a computational thinking taxonomy (CT-STEM Taxonomy) [10] consisting of four main categories which involve commonly applied computational thinking skills by STEM professionals, including: (1) data and information skills associated with generating, collecting, manipulating, analysing and visualizing data, (2) modelling and simulation skills including activities like understanding, using, assessing, testing and building or extending computational models, (3) computational problem solving skills such as troubleshooting, and debugging computing artefacts, assessing solutions to problems, applying problem solving strategies and creating abstractions, and finally (4) systems thinking skills consisting of investigating and visualizing systems, identifying relationships and levels of systems, and managing complexity. These four categories have been found to be intimately related to four category job functions and work tasks types in the same STEM areas, such as (1) ability to identify problems and specify constraints, (2) ability to design a model or system, build the model and develop experimental designs, (3) ability to verify the model, (4) ability to optimize the model and user interface to facilitate knowledge and discovery (see [11]). Additionally, other engineering education researchers [12] have identified several elements of computational thinking, including: familiarity with multiple software systems, ability to move between abstraction in software and physical systems, use of multiple CAD programs including 3D modelling, process simulation packages, numeric computational platforms, visualization tools, among others.

Specifically referring to the area of engineering, it focuses on the evaluation and usage of computation techniques and tools by applying or modifying existing numerical methods or methodologies to successfully solve problems. For this such tasks MATLAB has been found to be the most commonly used and desired software tool both in industry and academia [1] with as much as 6500 universities worldwide using it nowadays as their standard software for teaching, learning and research through a Total Academic Headcount (TAH) and other types of licenses.[3] On the other hand, one of the most relevant methods identified by experts in industry was for *Solving optimization or minimization problems in the form of optimal design, optimal control or inverse problems* [1], given that this methods enhance a solid ground for comparisons between multiple design scenarios, therefore improving decision making processes. Thus, the introduction of such methods for engineering solving problems from the very earlier educational backgrounds represent an excellent approach for engineering students to be integrated into a *Computational Thinking* environment under the CT-STEM Taxonomy.

In the case of reinforced concrete design courses for Civil Engineering education programmes, both undergraduate and graduate ones, it is required of extensive iterative calculations to analyse the structural efficiency of a design and even more to efficiently design one, due to the complex behaviour of reinforced concrete as composite material in comparison with other structural materials, like structural steel. Commercial software such as ETABS, RAM or Robot, aside of not always being fully available with licenses for students are mostly only capable to determine a required minimum reinforcement area of a predimensioned structural element such as a beam or column, and in some cases they could propose a list of potential rebar solutions, but still they are not really capable of proposing an optimum rebar design. As for foundation structures, there are even fewer commercial software that are actually capable of designing these such structures, given that their design process must consider the distribution of stresses in interaction with the supporting soil. In any case, the user must always verify any design proposal that a commercial software might compute, as it is one of the most important tasks of any Structural Engineer. Students are, therefore, constantly subject to frustrating calculation tasks and exercises, despite of the commercial software they may be using to help themselves, so that they often see a necessity to make their own computations and design processes, which is time consuming, specially when they might be faced by the programming factor which not all students may manage very well (even less in undergraduate programmes for which it is less likely to adopt such computational modelling simulation practices given the time and curriculum constraints just mentioned previously). Despite these factors and limitations, there are no excuses at this point to not integrate computed aided learning programs and computational modelling simulation practices in any educational engineering programme. Even though it may not be an easy task to carry on, there are numerous research works that propose different effective strategies and alternatives for this (see [1,8]), such as: modelling and simulation lab activities, introductory programming courses, computational modules embedded as projects or homework assignments, among others.

The present work has precisely the objective to contribute and support the implementation of such educational computation-based simulation practices for civil engineering programmes both in undergraduate and graduate education levels through the development of a computational MatLab Toolbox for numeric assessment and CAD visualization to teach and learn the art of designing reinforced concrete structures.

2. CALRECOD as a solution

CAL-RECOD is an interactive computer program for teaching subjects of structural reinforced concrete design and analysis using computational optimization methods-algorithms and mechanics of materials theory. The name CAL-RECOD is an abbreviation of *Computer Aided Learning of Reinforced Concrete Design*. The software can be used for different types of structural problems and cases, either for beams, columns, footings or structural frames composed by such elements. The idea of development of this software package was inspired by the CALFEM software package developed by the Division of Structural Mechanics of the Lund University [13,14]. Such software has been used internationally up to this point by researchers, academics and higher education students. Similar as CALFEM, it is expected that CAL-RECOD may reach international recognition and use, and continues development not only by members of the UAQ Engineering Faculty but internationally by anyone with the intention of contribution.

[3] See https://la.mathworks.com/academia/educators.html?s_tid=acmain_ep_gw_bod.

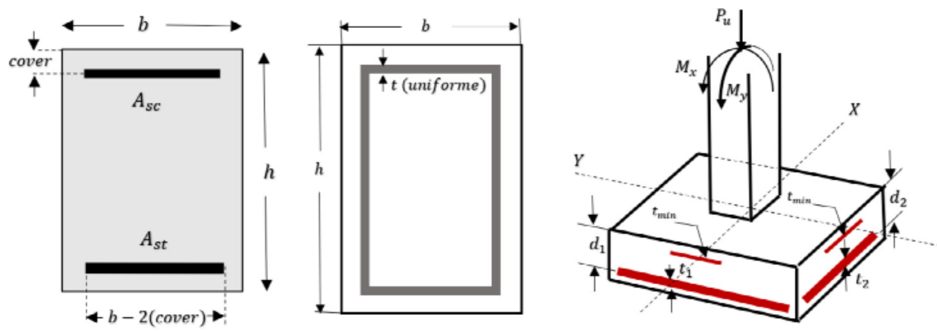

Fig. 1. ISR analogy for each type of structural element: (Left) Beam cross section, (Middle) Column cross-section, (Right) Isolated footing elements.

2.1. Functionality and interface

For each problem case and type of structure there are specific functions to assess a design efficiency or to design optimally either cross-section dimensions and/or its reinforcement. This way, users can compare their own designs with the optimal ones, given the specific problem case. Each function is adapted to a certain set of design specification criteria from the **ACI 318** code and/or the **NTC-17** Mexican code as a default basis, although each function is flexible for modifications of their design input parameters so that they may adapt to any requirement.

2.2. The Idealized Smeared Reinforcement (ISR) analogy

The optimization design processes are based on the ISR analogy [15] using the Steepest Gradient Descent (SGD) Method for a rapid determination of a required minimum reinforcement area, given an initial cross-section dimension under certain load conditions Fig. 1. This SGD optimization approach applies for all elements (beam, column and isolated footing elements) due to the concave form of their structural resistance efficiency in function of their reinforcement area when only a single variable of width for the ISR is considered (see Algorithm A.1 in Appendix).

2.3. Rebar optimization

The optimal design process of reinforcing bars depends on the structural element type case. For beams, a Linear-Search algorithm is used considering alternative reinforcement options regarding distribution of rebars in a particular cross-section, either of one individual rebar pack Fig. 2(a) or in vertical two-pack rebars Fig. 2(b), given that there is a limited number of potential solutions for this type of element based on its design mechanism (see Algorithm A.2 in Appendix). When a whole beam element is to be designed based on their flexure moments distribution diagrams, then three different cross-sections along the length of the element are to be designed (left end, middle and right end), considering cuts, free-clash and overlap reinforcement criteria Fig. 3 or simply designing each cross-section independently from one another.

Similar to beam elements, reinforcement in footings are usually just designed under pure flexure loads, therefore a Linear-Search algorithm is also used for these type of elements (see Algorithm A.3 in Appendix), considering an alternative reinforcement option of two-rebar packs disposed horizontally Fig. 4(b) when minimum separation restrictions do not suffice for the option of individual rebars Fig. 4(a).

For rectangular isolated footings the longitudinal bars are distributed according to the ACI-318 [16] and NTC-17 [17] design codes as shown in Fig. 5, uniformly in the smaller cross-section and non-uniformly in the longer one.

As for columns, two algorithms or design approaches are integrated. There are functions to design reinforcement both in an asymmetrical or

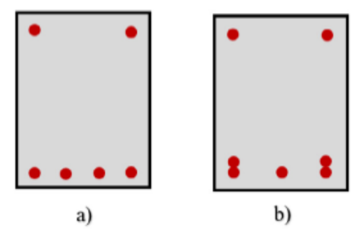

Fig. 2. Reinforcement bar options for a beam cross-section: a) in one-pack rebar layout, or b) in vertical two-pack rebars.

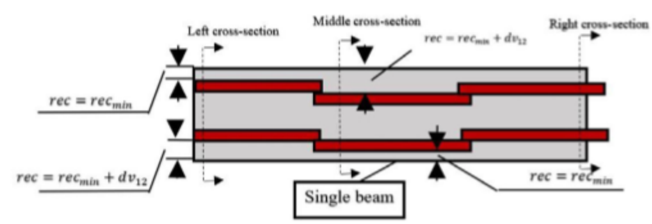

Fig. 3. Free-clash overlap reinforcement criteria for the design of beam elements along their length.

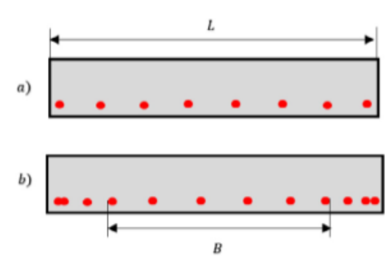

Fig. 4. Reinforcement bar options for a footing cross-section.

symmetrical fashion. When rebar in a symmetrical arrangement is to be designed then a Linear-Search approach is best suitable (see Algorithm A.4 in Appendix) as for beams. There are two options for symmetrical reinforcement in columns, either using one type of rebar for the whole arrangement or two Fig. 6

On the other hand, when an asymmetrical rebar arrangement is required, then the PSO algorithm takes place to reach an optimum option faster than with a Linear-Search approach, given that the number of rebar possibilities increases considerably for asymmetrical options. In order to minimize the *complexity factor of assembly* for construction of asymmetrical rebar arrangements, some simple restrictions are considered: namely that one type of rebar (not necessarily symmetrically placed) to a max of four different types of rebar could be placed simultaneously over a cross-section Fig. 7. Therefore, the max number of evaluations could be determined as $V_n^k = n^k$, corresponding to a

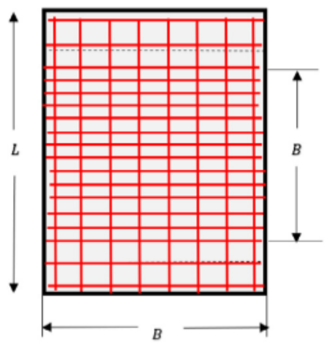

Fig. 5. Longitudinal rebar distribution over a rectangular isolated footing element.

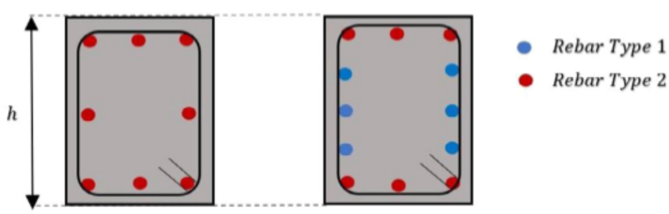

Fig. 6. (Left) Optimal symmetrical reinforcement design when only one type of rebar is considered, (Right) Optimal symmetrical reinforcement design when two different types of rebar are to be placed.

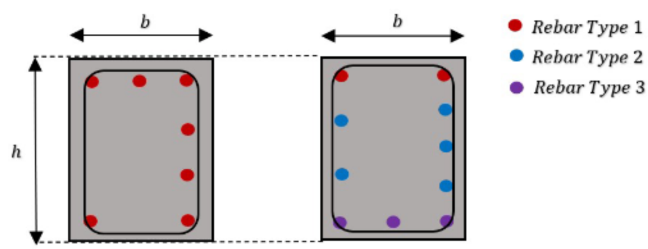

Fig. 7. Possibilities of reinforcement for an asymmetrical rebar configuration: (Left) with only one type of rebar and (Right) with as many as four different types of rebars.

combinatorial variation problem, in which n is the total number of different types of rebar commercially available (by default $n = 7$) (see Table 1) and k is the max number of repetitions in which each type of rebar could be placed over the cross-section ($k = 4$), therefore $V_n^k = 2401$ (which can highly affect the computational cost). However, with the aid of the PSO algorithm, the number of evaluations could be reduced to just 750 by using 25 particles in iterations (or time steps) as algorithmic parameters, still reaching great solutions in rebar area savings in comparison to symmetrical rebar arrangements. As mentioned previously, the optimal rebar designs are obtained from an optimal ISR with the SGD method. The optimization design process of asymmetrical rebar for columns is described in pseudo-code in Algorithm A.5 in Appendix).

The default rebar database is integrated with the following data Table 1 according to the most common commercial rebars in North-America, although it can be modified by any user.

2.4. Design of structural frames

There are also functions for the optimal design of structural frame systems for certain given initial element cross-section dimensions. At this point there are far more functions for the analysis of 2D frames rather than 3D. The functions hereby presented are able to analyse structural frames taking on account the detailed rebar on each element in a synchronized manner Fig. 8, out of a previous design, such that the mere self-weight of the reinforcement is considered in the analysis and even the initial dimensions for each element can be modified in case they are not fit for an optimal reinforcement design Fig. 9.

The way in which such designs are carried on are through sub-functions that execute design revisions tasks based on the *Strong Column - Weak Beam* criteria and beam–column node shear design. On the other hand, footings dimensions may be modified in case the initial ones do not comply with contact-pressure loads and shear criteria.

Table 1
Default rebar database.

Type (#)	*Diam* (in)	*Diam* (cm)	Area (cm^2)
#4	0.500	1.270	1.266
#5	0.625	1.587	1.979
#6	0.750	1.905	2.850
#8	1.000	2.540	5.067
#9	1.125	2.857	6.413
#10	1.250	3.175	7.917
#12	1.500	3.810	11.400

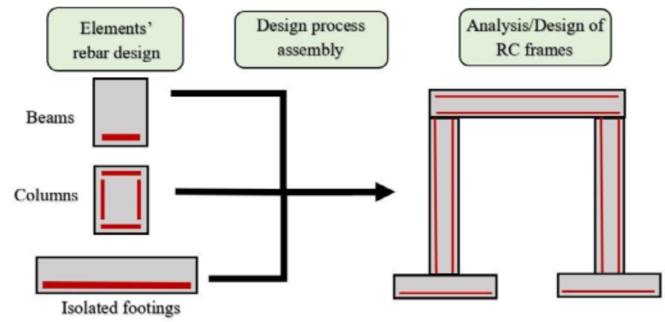

Fig. 8. Assembly design process of Reinforced Concrete frames.

2.5. Visual CALREDOC

As a complement of the CALREDOC MatLab toolbox, the development of a library in ANSYS SpaceClaim using Python language has been carried on as well. Such library aids the visualization of any resulting design using the main CALREDOC Toolbox through visual programming, so that a detailed evaluation of any design may be better carried out as CAD results. So far, the Visual CALREDOC library computes the visualization of 2D Concrete Frames and its elements' longitudinal rebar (composed only of beams, columns and isolated footings).

3. Functions and subroutines

It has been recommended by some authors [18] that in order to make a computed aided program pedagogical effective such program should be written in such a manner that all the usual subroutines related to the method in question are present; the student should be able to assemble all of such functions and operations so that a calculation is possible, without requiring a large amount of programming effort or computational skills. This way, a much more time-efficient learning environment is enhanced, requiring only for each student to build their own code for every problem to solve, instead of coding and programming the whole computational process with the risk of losing track in the run. Thus, the physical interpretation along with the solution strategy of any problem are continuously connected to the mathematical and numerical treatment of such problem at every moment.

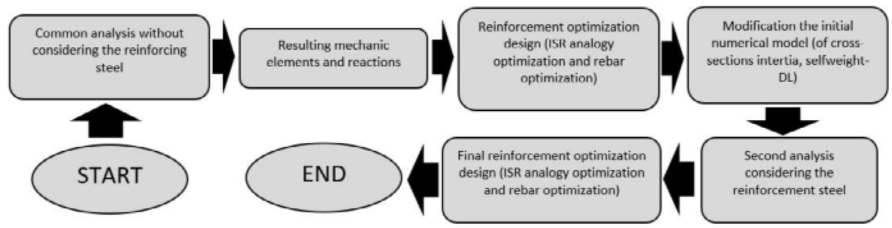

Fig. 9. Coupled design-analysis process for the structural frames considering optimal steel rebar reinforcement.

Table 2
Functions available organized in groups.

Function Group	Description
Structural mechanics	This group has the main objective of computing general calculations for the determination of mechanic properties of elements' cross-sections such as moment of inertia of cracked and non-cracked sections or resistance
ISR optimization	To determine an optimal reinforcement area for a given element cross-section dimension using either the SGD method or the PSO algorithm
Element rebar optimization	For the optimal design of configuration of rebar for any type of structural element (either through Simple-Search for beams, footings and symmetrical reinforcement in columns, or with the PSO for asymmetrical reinforcement in columns)
Design-Analysis of 2D frames	For the analysis-design of 2D frames as a coupled process. Available functions include static linear and non-linear analysis and dynamic static linear analysis. Some functions work through a CALFEM function(s)
Graphic functions	For plotting of reinforced designed cross-section, interaction diagrams for columns, optima design convergence graphics, etc
Visualization functions	Functions in python language for ANSYS SpaceClaim for the visualization of designs using the main CALRECOD MatLab functions

In general, all of the available functions of CALRECOD[4] can be organized in six different groups as described in Table 2:

4. Illustrative examples

In this section it will be demonstrated through illustrative examples how versatile can CALRECOD be as an interactive educational tool to guide students on their way to learn how to design more effectively reinforced concrete structures. For instance, it could be of interest to determine what would be the optimal reinforcement area on each cross-section boundary of any specific structural element so that a required structural efficiency range may be complied against certain load conditions, or to analyse the structural efficiency of a rebar arrangement on an element's cross-section. And going further for structural frames, it could be of interest for students and users in general to determine the structure's weight and the total weight of each of its material components, or perhaps it would be interest to estimate initial construction costs. All of these and many other functions are included in CALRECOD and have great aid-learning potential. As following, a few illustrative examples will be shown case, regarding both analysis and design functions as well as the use of graphics to aid design and analysis interpretation along with visualization of designs in the 3D space through CAD ANSYS SpaceClaim software.

4.1. Optimal reinforcement area in structural elements

Let us consider the beam cross-section of dimensions $b = 20$ cm, $h = 40$ cm, concrete cover along the width dimension of 4 cm and concrete cover along the height dimension of 3 cm, a $f'_c = 280\ \frac{\text{Kg}}{\text{cm}^2}$ will be used. Only one cross-section will be analysed under the load condition of 15 Ton m of pure flexure. A requirement of high ductility over the cross-section is considered. Results yield an optima ISR as shown in Fig. 10, with an optima ISR width of 1.01 cm and a corresponding reinforcement area of 12.18 cm^2, with a structural efficiency of $0.989 = 98.9\%$. As it is observed, the optima convergence depicts how the structural efficiency varies as the reinforcement quantity changes, which is very useful. The **function SGD1tBeamsISR** was used.

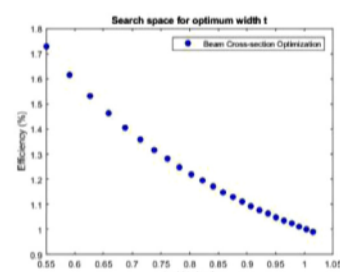

Fig. 10. Convergence of the optimal width t of the ISR in relation with the structural efficiency of the beam cross-section.

4.2. Structural efficiency of a design proposal for a column cross-section

Let us consider the column cross-section of dimensions $b = 40$ cm, $h = 50$ cm reinforced with rebars of $No.$ #6 of diameters $\frac{6}{8}$ inches distributed symmetrically over the cross-section (3 rebars along the width dimension and 4 rebars along the height dimension), width a concrete cover of 4 cm over all four section boundaries, using concrete of $f'_c = 280\ \frac{\text{Kg}}{\text{cm}^2}$. Results yield a structural efficiency of $1.48 = 148\%$ with neutral axis depths of $[11.24\ \text{cm}, 7.26\ \text{cm}]$ for X and Y axis directions, respectively. The reinforced cross-section plot and interaction diagrams are shown in Fig. 11, indicating that the design is not efficient, and more reinforcement should be used. The **function RebarDisposition** was used to compute the rebar local coordinates over the cross-section,

[4] For more reference of the content and calculations of all functions, see its documentation at CALRECOD's GitHub repository: https://github.com/calrecod/CALRECOD.

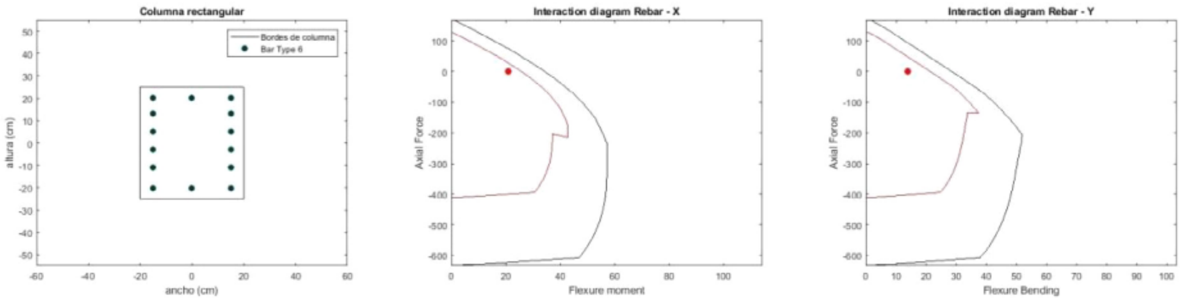

Fig. 11. (Left) Reinforced concrete cross-section design of the column. (Middle) Interaction diagram in the X direction, (Right) Interaction diagram in the Y direction.

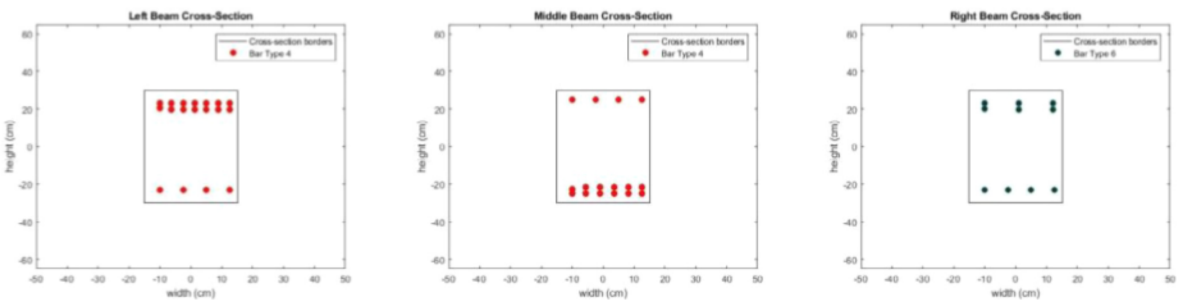

Fig. 12. Reinforced concrete cross-section designs for the beam along its length (left, middle, right), respectively.

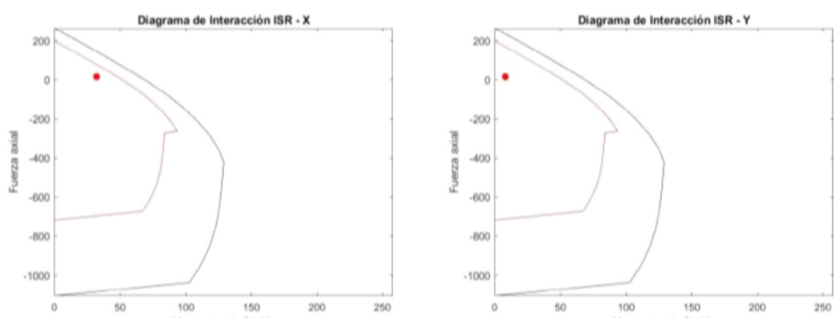

Fig. 13. Optimal reinforced concrete cross-section design of a column. (Left) Optimal ISR Interaction diagram in the X direction, (Right) Optimal ISR Interaction diagram in the Y direction. A minimum reinforcing ISR area of 62.66 cm^2 was obtained, with a structural efficiency of 92.12%.

function diagramasDisposicion to compute the interaction diagrams and structural efficiency, and **function diagramsFinalRebarCols** was deployed to plot the design results.

4.3. Optimal designs of reinforced concrete elements

In this section, complete cross-section optimization problem examples will be regarded, showing case the quality of results to enhance a solid platform for comparison of designs' performances in relation with standard non-optimal designs.

Beams:

Let us consider a reinforced concrete beam of length equal to 500 cm and cross-section dimensions of 30×60 cm, made of concrete $f'_c = 280\ \frac{\text{Kg}}{\text{cm}^2}$ subject to load conditions of 33 Ton m, 29 Ton m, 31 Ton m for all of its three main cross-sections along its length (left, middle, right), respectively. A lateral concrete cover of 3 cm with a high demand of ductility. By using the **Function: beamsISR** results are: (see Fig. 12).

Columns:

Let us consider the reinforcement design of a columns with cross-sections $b = 60$ cm, $h = 60$ cm of $height = 400$ cm made of concrete $f'_c = 280\ \frac{\text{Kg}}{\text{cm}^2}$ subject to load conditions of $Pu = 15$ Ton, $Mu_x = 32$ Ton m, $Mu_y = 8$Ton m with concrete cover in the vertical and horizontal cross-section direction of 4 cm. A cross-section *Cracked* mechanisms will be considered in case it is necessary. It is required a high ductile behaviour of the cross-section. No slenderness effects are considered. By using **Function:isrColumnsSymAsym** results are:

Symmetric reinforcement: (see Figs. 13 and 14).

Asymmetric reinforcement: (see Figs. 15 and 16).

Isolated footings:

Let us consider the reinforcement design of an isolated footing supported by a soil of admissible load equal to 2.5 $\frac{\text{Kg}}{\text{cm}^2}$ with a Safety Factor of 1.5, that supports a column of cross-sections $b = 30$ cm, $h = 50$ cm that transmits biaxial loads of $Pu = 20$ Ton, $Mu_x = 35$ Ton m, $Mu_y = 24$ Ton m, made of concrete $f'_c = 300\ \frac{\text{Kg}}{\text{cm}^2}$, with concrete cover in the vertical and horizontal cross-section direction of 5 cm. It is required a high ductile behaviour of the transversal cross-sections. By using the **Function: isrFootings** results are: (see Fig. 17).

4.4. Analysis-design of RC frames and visual CALRECOD

CALRECOD, by being able to design optimally the elements' reinforcement of entire plane frames, it could take a reinforced concrete design course's scope to another level, as students could realize more

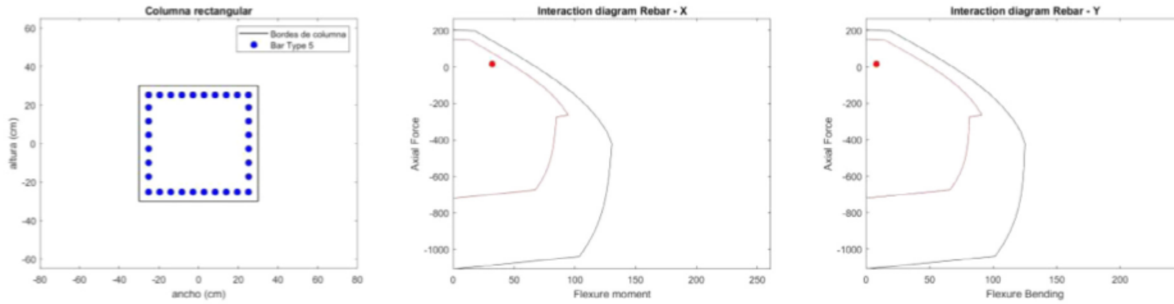

Fig. 14. Optimal reinforced concrete cross-section design of a column. (Left) Optimal Rebar Interaction diagram in the X direction, (Centre) reinforced concrete column cross-section, (Right) Optimal Rebar Interaction diagram in the Y direction. A minimum rebar area of 63.34 cm^2 was obtained, with a structural efficiency of 92.71%.

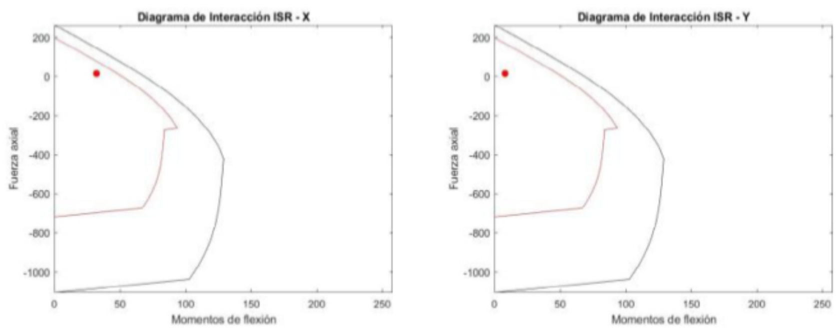

Fig. 15. Optimal reinforced concrete cross-section design of a column. (Left) Optimal ISR Interaction diagram in the X direction, (Right) Optimal ISR Interaction diagram in the Y direction. A minimum reinforcing ISR area of 62.66 cm^2 was obtained, with a structural efficiency of 92.12%.

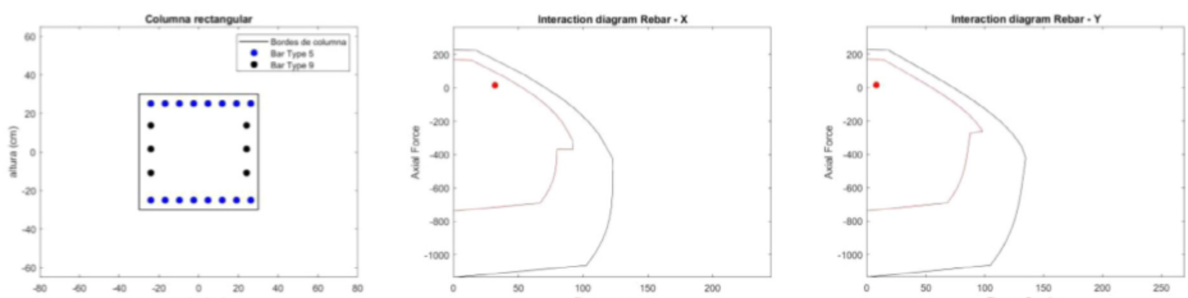

Fig. 16. Optimal reinforced concrete cross-section design of a column. (Left) Optimal Rebar Interaction diagram in the X direction, (Centre) reinforced concrete column cross-section, (Right) Optimal Rebar Interaction diagram in the Y direction. A minimum rebar area of 70.14 cm^2 was obtained, with a structural efficiency of 87.02%.

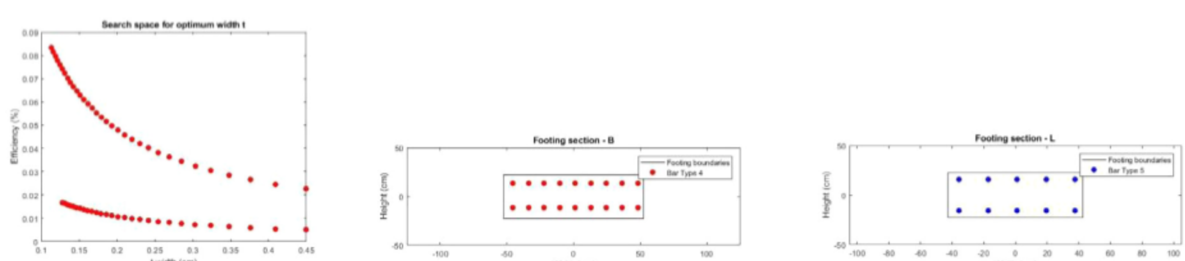

Fig. 17. Optimal reinforced concrete cross-section design of an isolated footing. (Left) Optimal ISR convergence with the SGD method, (Middle) Optimal reinforced transversal cross-section along the L dimension, (Right) Optimal reinforced transversal cross-section along the B dimension.

complete projects and assignments of entire structural systems considering more complex mechanical behaviours (in the non-linear plastic range, for instance), which could enhance their academic and professional background. In this subsection, an example for a plane frame will be shown case, presenting also the results that may be obtained through the VISUAL-CALRECOD functions.

Let us consider the following structural plane frame of Fig. 18. A $f'_c = 300 \ \frac{\mathrm{Kg}}{\mathrm{cm}^2}$ for all elements (including isolated footings) will be considered. An admissible bearing load capacity of soil of $q_{adm} = 2.5 \ \frac{\mathrm{Kg}}{\mathrm{cm}^2}$ is considered for the design of the isolated footings, with a Safety Factor $FS = 2.0$.

The computation of lateral equivalent shear base forces for each floor subject to a ground pseudo-acceleration of 200 $\frac{\mathrm{cm}}{\mathrm{s}^2}$ takes place.

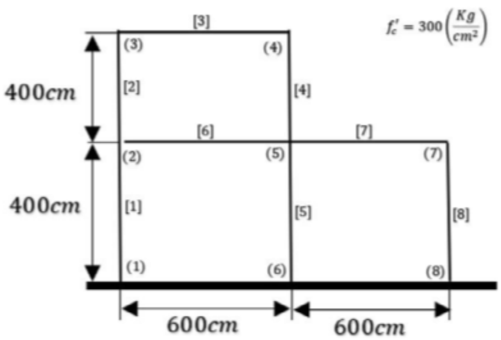

Fig. 18. Topology of the illustrative structural frame.

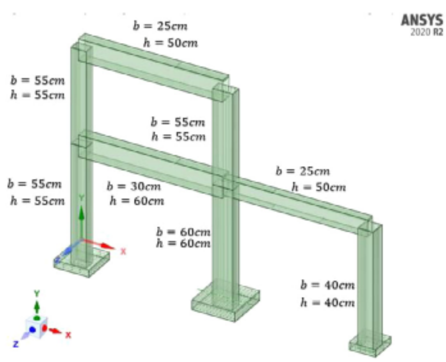

Fig. 19. Dimensions of the structural frame's elements.

The initial dimensions shown in Fig. 19 remain constant through the optimization design process with asymmetric reinforcement in the columns. The **Function: DesignRCPlaneFrameBCIF** is used. The obtained results with the use of VISUAL-CALRECOD are shown in Fig. 19 and Fig. 20:

5. Discussion of results

The results obtained with the use of the CALRECOD functions in MatLab both graphical and numerical are of great quality and could aid very well as a solid learning base of structural mechanic subjects and for the design of reinforced concrete structures. Students and users in general, aside of obtaining a solid base of comparison with optimal designs, could explore themselves with various reinforcement configurations and design solutions, and apply their own criteria to elaborate more efficient work, being able to even contribute and propose new ideas for the further development of CALRECOD once they dominate its functions and interface, which is one of the main objectives of CALRECOD.

5.1. Comparison with commercial software

It does not matter which commercial software might be used for the design of concrete structures, it would be practically impossible to make any adjustment in the design processes of the software and even to be able to take a look at what sort of computations take place. In any case, as it was mentioned before no known commercial software up to this point is able to optimize their rebar design proposals and even less to deliver a whole structural iteratively design assessment resume. One example is ETABS, developed by Computers & Structures, Inc,. Even though ETABS is currently one of the most deployed software of structural design and analysis in industry, it is only capable to determine a required reinforcing area quantity, either for beams or column elements (which is what CALRECOD computes through the ISR analogy), it cannot propose rebar designs nor to analyse the structural efficiency of design proposals given by the user. Anyone who has ever used this such software would agree with these statements. Nonetheless, when comparing results of CALRECOD's with ETABS's or any other software's regarding this such reinforcing area quantities, it would be found that they are very similar. The reason of them not to be equal is for obvious reasons of approximate parameter values, and even the way in which computations take place iteratively, as well as the structural efficiency ranges required from one software to another (from 1 to 100%). Therefore, it was considered pointless to try to make direct comparisons of software outputs in this paper through screen-shots or brief delivery resumes, despite of how much the authors would have liked to do so, besides one of the primary objectives of CALRECOD is that students are capable to better compare and assess their designs outcomes from CALRECOD to their own computations and to what commercial software delivers, as an aid tool throughout their learning process. It would suffice to mention what CALRECOD is capable of doing and how it does it in comparison with what other software is capable too. Moreover, CALRECOD's computed code is totally transparent and available for consulting and modification by users[5] at any point in their design and analysis tasks.

5.2. Recommendations and proposals

With the CAD visualization functions of VISUAL-CALRECOD along with the graphical functions in MatLab Calculation Memories could be rapidly developed, as well as construction detailed plans, which would be of great advantage and beneficial for Students and Professors of courses related with reinforced concrete design and structural mechanics in general in higher education; more topics on such courses could be taught in comparison with standard courses programs with common educational practices, thus more elaborate academic projects and assignments could be considered to realize for the courses in which CALRECOD is adopted.

In relation with the adoption of commercial software tools for the aid in teaching of reinforced concrete design courses, such as Sap 2000, RAM8elements, among others., CALRECOD offers a more versatile, dynamic and transparent interface, in which all functions content and the calculations they compute can be fully appreciated in detail by users and could be even be slightly modified (carefully done), enhancing the scope of teaching and learning programs of such courses, requiring therefore, to adjust the current programs content with new educational strategies when CALRECOD is adopted for each subject. In the following flow-diagram of Fig. 21 is shown precisely a proposal for the adoption of a new work scheme in higher education for courses in which CALRECOD is used.

As it is observed in the flow diagram, theory and manual design calculations would still be present for every new topic, although only at the very beginning during the introduction stage. However, from that point on, CALRECOD would take place through a Computer Lab module, in which students can elaborate their own functions along with the CALRECOD functions content and theory so that a more solid base of comparison for their projects and assignments can be laid out; is at this stage in which the advantages of CALRECOD to compute optimal designs takes form, so that students could enhance and maximize their abilities not only of computation and programming, but also of engineering problem solving skills.

[5] Some tutorial visual examples and videos are already available in CALRECOD's official Youtube Channel: https://www.youtube.com/channel/UCRcDweFXNxsT1JBR8U0OLtQ.

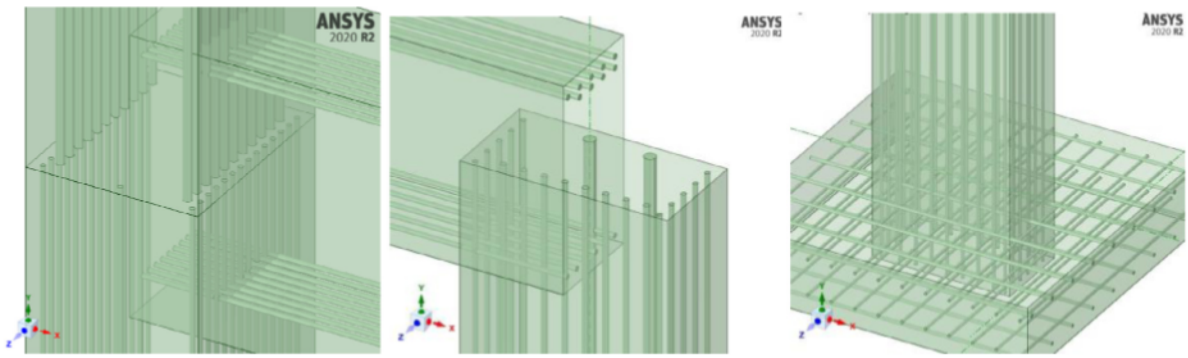

Fig. 20. (Left) Detailed reinforcement in the node (2), (Middle) Detailed reinforcement in node (7), (Right) Detailed reinforcement in node (6).

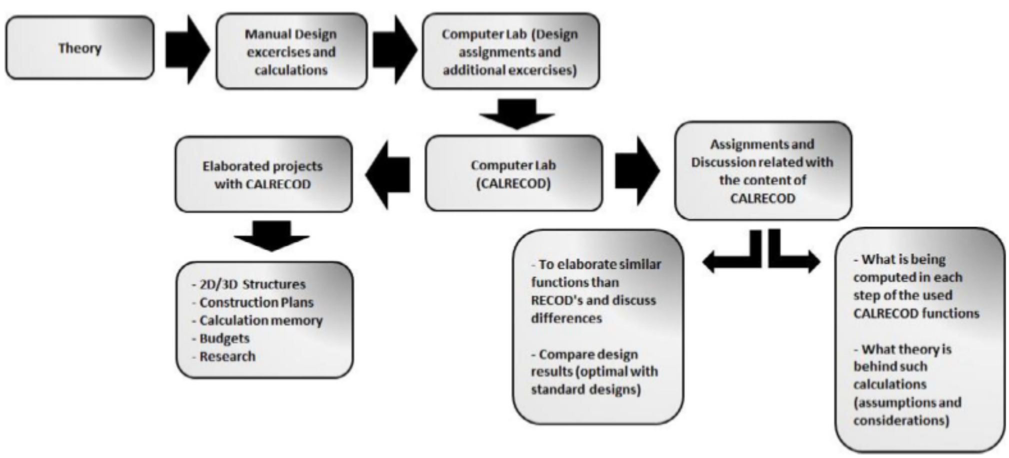

Fig. 21. Proposal of teaching program of a reinforced concrete design course.

5.3. Future work

One of the advantages of this such software is that it can be further developed not only by its owner but worldwide by anyone willing to contribute. The creation of a Blog or repository is necessary for the contributors to send their proposals so that such proposals may be thoroughly reviewed. It is expected that new CALRECOD functions in MatLab are developed in the upcoming years regarding the design of transversal reinforcement (stirrups), and 3D frames, applicable for other types of structural elements (such as slabs, continuing footings, etc.), free-clash reinforcement function in element unions (beam–column, column footing, slab-bams, etc.). All of these developments along with the creation of new ANSYS-SC script functions for the VISUAL-CALRECOD library.

On the other, regarding the efficiency of using CALRECOD in Higher Education engineering programs, it would be important to elaborate simulations in long-term courses of reinforced concrete structures design with the used of CALRECOD and without it, as well as the formulation of interviews for the participants regarding their opinions, suggestions and recommendations after having used CALRECOD, so that a more reliable comparison framework could be laid out to stress the effectiveness of such software.

6. Conclusions

Through this work is has been demonstrated that the integration of CALRECOD as a computational tool for reinforced concrete structures design courses could be of great advantage and beneficial both for research and academics in higher education, even for industry. In resume, the main potential benefits and advantages to be obtained with the use of CALRECOD are enlisted as the following:

1. Students are stimulated with new ideas given the existing routines in the programming learning environment, and are therefore more likely to develop new research
2. Students obtain a better understanding of the material modelling aspects and the numerical issues involved without getting confused in the process regarding basic matters
3. Students enhance their learning potential to model complex problems in a simple manner, acquiring and improving real problem-solving skills

On the other hand, regarding the software impact, it has been proven that with CALRECOD, students could enhance those most common abilities and skills required by industry in the STEM areas, not only because CALRECOD's strategy of implementing optimization design procedures, but also because of its whole dynamic work environment (IDE) that takes the most of students to improve their computation modelling and programming skills.

In this era of technology, it is time for educators to start to implement with the best strategies computational technological tools for the aid in teaching and learning, preparing students as best as possible for the industry and research environment (specially in the STEM areas) in which they will be immersed. CALRECOD promises a great deal in this regards for civil engineering courses of structural mechanics of reinforced concrete structures.

CRediT authorship contribution statement

Luis Fernando Verduzco: Conception and design of study, Acquisition of data, Analysis and/or interpretation of data, Writing – the original draft, Writing – review & editing. **Jaime Horta:** Conception and design of study, Acquisition of data, Analysis and/or interpretation of data, Writing – review & editing. **Miguel A. Pérez Lara y Hernández:** Analysis and/or interpretation of data, Writing – review & editing. **Juan Bosco Hernández:** Analysis and/or interpretation of data.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Pseudo-codes of algorithmic design-analysis processes

A.1. The idealized smeared reinforcement analogy

Algorithm A.1: Pseudo-code: Steepest Gradient Descent method (SGD-ISR-1t)

BEGIN
for Nmodels=1:nm
$t_k = inital \rightarrow t_0$
Compute $f(initial \rightarrow t) = f(t_k)$
While $f(t_k) > rango_{sup}$ **or** $f(t_k) < rango_{inf}$
Compute $g(t_k) = \nabla f(t_k)$
Compute search direction p_k
if $f(t_k) < rango_{inf}$
$p_k = 1$
else if $f(t_k) > rango_{sup}$
$p_k = -1$
End if
Update the current $t_{k+1} = t_k + \alpha_k(p_k)$
$\alpha_k = -\frac{g(x_k)}{||g(x_k)||}$
Compute $f(t_{k+1})$
k=k+1;
End While
$t_{final} = t_k$
$f_{final} = f(t_k)$
End for
END

A.2. Optimal rebar design for beams

Algorithm A.2: Algorithmic design process en pseudo-code for the optimization of rebars in rectangular beams' cross-sections.

BEGIN
1.- Apply the Steepest Gradient Descent method to obtain an optimal width t **(optimal** $A(t)$ **from which to begin the rebar design process)**
2.- To determine the required number of rebars n **for each of the 7 different rebar types available, such that** $A_{var} \geq A(t)$ **complies**
3.- To optimize the rebar arrangement over the cross-section, either in individual rebar packs or 2-rebar packs. The restriction $sep \geq sep_{min}$ **must be complied at all times**
For i=1 to nTipos-Var=7
Verify if $sep \geq sep_{min}$ for individual rebars in one horizontal rebar layout
End For
Choose the option with minimum reinforcement area
If $sep \geq sep_{min}$ **for each option, then:**
Do
Transform the optimal reinforcement area previously found into a rebar horizontal arrangement in packs of 2
While $sep \leq sep_{min}$
Else
Increase section's height $h = h + 5cm$
End If
END

A.3. Optimal rebar design for isolated footings

Algorithm A.3: Algorithmic process in pseudo-code for the optimization of rebar in a rectangular isolated footing's cross-section.

INICIO
1.- Apply the Steepest Gradient Descent method to obtain an optima width t **of the ISR (optimal** $A(t)$ **from which to begin the rebar design process)**
2.- Determine the required number of rebars n **for each of the 7 different rebar types available, such that** $A_{var} \geq A(t)$
$n_{var} = \frac{A(t)}{a_v}$
$A_{var} = n_{var}a_v$
$sep_{var} = \frac{a_v b}{A_{var}}$
3.- Apply simple-search to obtain the better design option, such that $A_{var} \rightarrow A_{min}$ **and** $sep \geq sep_{min}$ **comply at any moment**
Evaluate the structural efficiency
Evaluate construction cost
FIN

A.4. Optimal rebar design for columns

Algorithm A.4: General algorithm for the optimal design of symmetric reinforcement in a rectangular column cross-section with only one type of rebar (SGD-1t-ISR-SimpleSearch)

BEGIN

1.- Execute Steepest Gradient Descent method to find t **optimum** A_t **to begin rebar optimization**

2.- Determine the maximum number of rebars horizontally and vertically for each type of rebar

For i=1 to n-rebar-types=7

$maxRebarHorizontal = \frac{(b-2(cover))+sep_{min}}{sep_{min}+d_b}$

$maxRebarHorizontal = \frac{(h-2(cover))+sep_{min}}{sep_{min}+d_b}$

Determine the minimum number of rebars horizontally

$minRebarHorizontal = [\frac{1}{2}(n-2(maxRebarHorizontal)) \geq 2]$

Search over all the possible rebar arrangements

For $j = minRebarHorizontal$ **to** $maxRebarHorizontal$

Evaluate structural efficiency $Eff < 100\%$

Evaluate $cost < cost_{min}$

End For

Save the option with lowest structural efficiency among the most economical

End For

If $sep \geq sep_{min}$ is not complied for any option, then:

The column height is increased $h = h + 5cm$

End if

END

Algorithm A.5: General algorithmic process for the optimal design of asymmetric rebar in a column cross-section from the SGD-ISR-1t (SGD-1t-ISR-PSO-4Rebar)

BEGIN

1.- Execute Steepest Gradient Descent method to find t **optimum** A_{t_1}, A_{t_3} **to begin rebar optimization**

2.- Determine all possible rebar combinations

For each A_{t_i}:

Check $n_j a_{b_j} \geq A_{t_i}$

$sep \geq sep_{min}$

$face \rightarrow rebar - type : [4, 5, 6, 8, 9, 10, 12]$

$number - rebars : [n_1, n_2, n_3, n_4, n_5, n_6, n_7]$

$n \geq 1$

3.- Optimize the combination

PSO-algorithm

For i=1:numberParticles

Initial positions for each particle ($combo - rebar = [k_1, k_2, k_3, k_4]$)

k_j takes a value between [1,7] (number of available rebars)

$x_{ij} = combo_{ij} = combo_{min} + r(7-1)$

$v_{ij} = \frac{\alpha}{\Delta t}(-\frac{7-1}{2} + r(7-1))$

End For

For i=1:numberIterations

For i=1:numberParticles

Evaluate $Eff < 100\%$ and $sep_j \geq sep_{min}$

Minimize cost $cost_i < cost_{min}$

End For

For i=1:numberParticles

Update positions and velocities

$v_{ij} = v_{ij} + c_1 q(\frac{combo_{ij}^{pb} - combo_{ij}}{\Delta t}) + c_2 r(\frac{combo_j^{sb} - combo_{ij}}{\Delta t})$

$x_{ij} = combo_{ij} \rightarrow combo_{ij} + v_{ij}\Delta t$

End For

End For

End PSO-algorithm

if $best - position \neq 0$

$h = h + 5$

Repeat step 3

End if

4.- Extract best combo $combo_{best} = [k_1, k_2, k_3, k_4]$

END

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