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Research Article

1D fuzzy inverse logic method and its use in the design of thick reinforced concrete columns

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ABSTRACT

In this study, without using any uniaxial force and bending moment (N-M) interaction diagrams, designs were carried out on thick columns subjected to uniaxial bending and compression by a novel 1 dimensional (1D) Fuzzy Inverse Logic (FIL) method. For this purpose, firstly, a Fuzzy Logic (FL) model was developed and the FIL method was applied to it thereafter. While, the cross-section width (*b*), the cross-section height (*h*), the rebar diameter(*f*), the numbers of reinforcement rows (R_x and R_y) placed into the cross-section in X and Y directions, the characteristic concrete compressive strength(f_{ck}) and the axial force ratio $N_r=N/(b.h.(f_{ck}/1.5))$ were taken as variable parameters, concrete cover thickness (*c*), rebar strength (f_{yd}) and k_1 parameter defined for the concrete pressure block were kept constant in the developed FL model. After designs were performed on 15 columns having different variable variations by the 1D FIL method, moment bearing capacities of the obtained 9737 alternative designs determined conventionally were compared with the desired moment values. The evaluations made on the comparisons show that the FIL method is not only a very effective artificial intelligence method for the design of reinforced concrete thick columns but also a promising method for many other problems such as control, optimization, design, etc.

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INTRODUCTION

In the design of reinforced concrete columns subjected to uniaxial bending and compression, the N-M interaction diagrams are generally used. It is possible to come across many different of these diagrams constituted depending on parameters such as reinforcement strength, number of reinforcement rows, concrete cover thickness, and section dimensions in technical literature. However, a lot of different interaction diagrams for different reinforcement ratios are usually given in only one graph. Therefore, in a design of a reinforced concrete column; using the correct N-M interaction diagram and reading the numerical reinforcement ratio accurately and precisely have great importance for the accuracy of the design. In the computer-aided column designs, the moment capacity of a column of which cross-section and material properties are defined previously is computed firstly and then this moment capacity is compared with the moment obtained from static

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analysis. In case it is detected in the comparisons that the column design is insufficient or not economical, the column cross-section is revised and the capacity moment is recomputed. In this way, the final column design is completed by making many computations by trial and error method. Considering that these processes are carried out for all columns in a building, it can be easily understood that quite a bit of time is required to complete a good and quality building design.

Recently, studies on structural elements such as beams, columns, etc. in reinforced concrete structures have been performed by many artificial intelligence techniques as well as analytical methods. Among these techniques, artificial neural networks, genetic algorithm, fuzzy logic, etc. are the most known techniques in the technical literature [1-6].

When the studies carried out by the FL method in the field of civil engineering are examined, it is understood that such studies can be classified under three headings in general. The first heading covers the studies carried out for the estimation of capacity, strength, displacement, deformation, some coefficients in structural computations, behavior, etc. based on element, material, and structure [7-15]. The second heading includes the studies in which assessments such as fire, seismic, condition, damage, performance, and capacity were made [16-20]. Finally, the third heading includes the studies on monitoring [21], crack diagnosis [22], classification of damages [23], parameter ranking [24], crack identification [25], response control [26], structural control [27], selection of construction systems [28], optimization [29] and etc. Studies on design with FL are very few [30]. On the other hand, the design studies carried out by FL so far do not cover a complete design procedure but include estimation(s) of certain parameters or a few parameters in the design with the help of known ones. From this point of view, current design studies carried out by FL can be examined in the 1st group classification.

Due to the nature of FL computations, determining the geometric dimensions, the material to be used, and the amount and arrangement of reinforcement for a structure or structural element under certain loads are very difficult. Because the parameters that should be determined in the design are also the parameters that should be used as inputs for the design. Therefore, designs are usually made by trial and error method with the values of some design parameters assumed or estimated previously in conventional computations.

In this study, designs of thick columns subjected to uniaxial bending and compression with the 1D FIL method which is fully compatible with the basics of FL [30,31] are aimed. For this aim, after giving general information about the FL method, the FIL method, and Thick columns subjected to uniaxial bending and compression, the computation logic of the FIL method in 1D has been explained in detail. Then, by applying the 1D FIL method to the FL model developed to determine the moment capacities of thick columns, designs were performed for 15 different thick columns. Finally, the accuracy and precision of the thick column designs performed with the 1D FIL method have been verified by comparing them with conventional capacity calculations. Briefly, the novel 1D FIL method, which can directly use the data of a fuzzy model on which it is applied, is presented in this study as an alternative to the design graphics, solution charts, trial and error techniques, etc. used in the solutions of the problems such as engineering designs in which the problem variables (inputs) are tried to be determined to obtain the desired output.

A BRIEF INFORMATION ABOUT FUZZY LOGIC (FL)

The working principle of the FL method is based on searching for solutions for different input values in the fuzzy output data of a problem that has been solved and experienced with a sufficient number of examples before and whose inputs and outputs have been transformed into fuzzy expressions. For this, the input parameter values for new FL computations must remain within the value ranges of the input parameters in the current solutions. The computation logic of the FL is based on unclear (fuzzy) propositions used in linguistic expressions [33,34]. To apply the FL method to a scientific problem in which net output values are investigated, the value ranges of input and output parameters must be fuzzified by classifying them into fuzzy sets first. These fuzzy sets are used as input and output parameters in fuzzy propositions. In fuzzy computations, membership degrees of the net values of the input parameters are determined with the help of membership functions. The membership degrees and fuzzy sets corresponding to the net values of the input parameters are passed through the relevant fuzzy propositions in the rule base which contains all fuzzy propositions and fuzzy outputs. Finally, obtained fuzzy outputs are converted into net outputs using an appropriate defuzzification method. All of the processes in FL are summarized in Figure 1. Since FL has widespread use, its validity has already been proven and much more details about it can be easily found in the literature [35-37], comprehensive information about it was not given in this study. On the other hand, because the FIL method was developed on the basis of the FL method, the required information about both methods is presented in the headings below.

In the defuzzification processes of FL, different defuzzification methods can be used to compute net outputs. The Weighted Average Method (WAM) [38] expressed by Eq. (1) is one of the defuzzification methods and is used as the defuzzification method in the FIL method.

$$O_{net} = \frac{\sum_{i=1}^{n} O_i . \mu_i}{\sum_{i=1}^{n} \mu_i} \quad (1)$$

In Figure 2, fuzzy outputs in an FL model with two input parameters such as $X=A_{input}$ and $Y=B_{input}=B_j$ were shown. The net B_{input} value of the variable Y has membership only

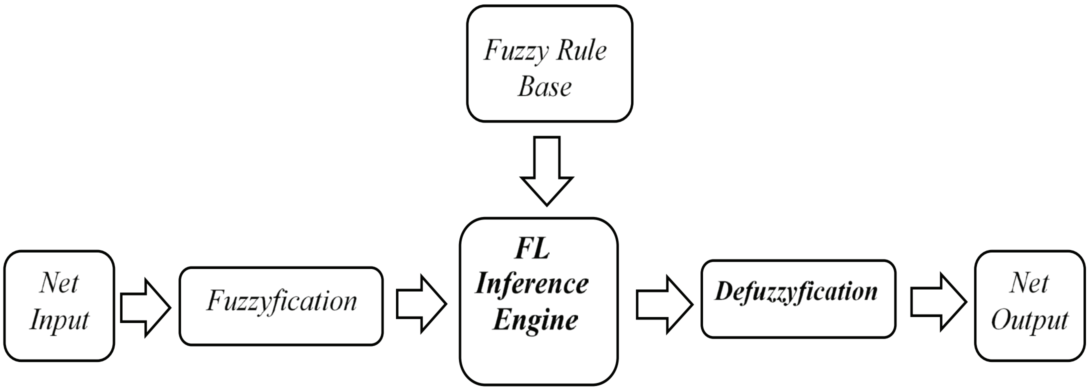

Figure 1. Flowchart of Fuzzy Logic.

in the B_j fuzzy set and its membership degree is $m(B_j)=1$. On the other hand, the net A_{input} value of the X variable has memberships in both the A_i and A_{i+1} fuzzy sets, and its membership degrees in these sets are $m(A_i)<1$ and $m(A_{i+1})<1$ respectively. When the WAM method was applied to the FL model given in Figure 6 and if the condition term of "*AND*" was used in FL rules then the net output can be obtained by Eq. (2).

$$O_{net} = \frac{O_{j,i}\times \min\left(\mu_{(A_i)};\mu_{(B_j)}\right)+O_{j,i+1}\times \min\left(\mu_{(A_{i+1})};\mu_{(B_j)}\right)}{\min\left(\mu_{(A_i)};\mu_{(B_j)}\right)+\min\left(\mu_{(A_{i+1})};\mu_{(B_j)}\right)} \quad (2)$$

Since a relationship given by Eq. (3) can be written between the membership degrees of $m(A_i)$ and $m(A_{i+1})$ for triangular membership function, a more simplified Eq. (4) can be used to compute net output instead of Eq. (2) in FL computations.

$$\mu(A_i) + \mu(A_{i+1}) = 1 \quad (3)$$

$$O_{net} = O_{j,i} \times \mu_{(A_i)} + O_{j,i+1} \times \mu_{(A_{i+1})} \quad (4)$$

As can be understood from Eq. (4), the net output value can be computed by multiplying the rule outputs with the $m(A_i)$ and $m(A_{i+1})$ membership degrees of the X parameter.

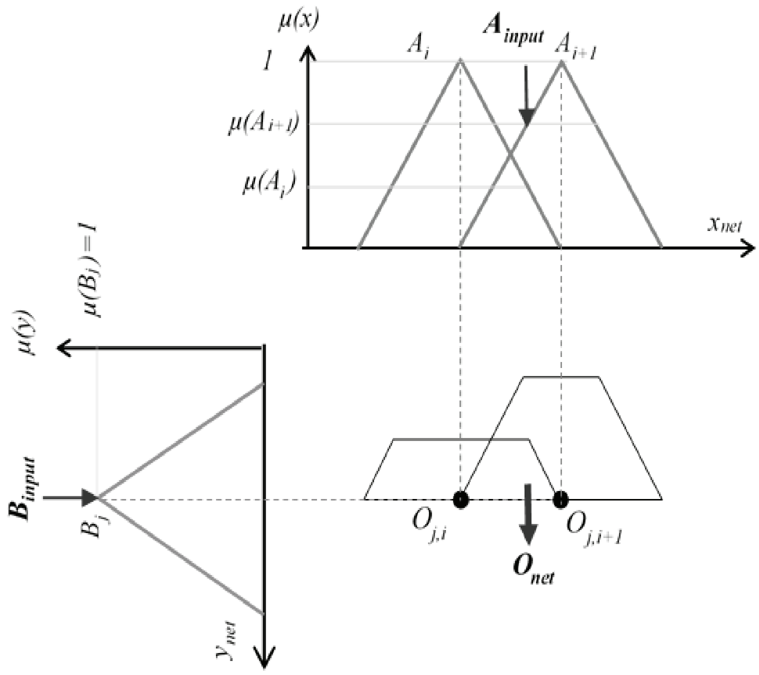

Figure 2. Fuzzy outputs obtained from FL computations.

Thick Columns Subjected to Uniaxial Bending and Compression

In general, columns in buildings are often exposed to both biaxial moment and normal force *(M_x+ M_y +N)* effects. From time to time, combined uniaxial moment and axial force *(M_x+N or M_y+N)* act together on the columns in the edge frames of buildings. However, computations made on columns under uniaxial bending and compression are important as they are used as a part of some methods preferred for the computations of columns under biaxial bending and compression. Column designs or computations of moment-bearing capacities of columns are performed differently depending on columns' slenderness. Since thick columns are the subject of this study, design computations and moment-bearing capacity computations about slender columns are not included in the scope of this study.

Generally, similar computations are performed for the determination of moment bearing capacity and for design in thick columns subjected to combined bending and compression. In the first of these, the maximum moment that can bear by the column is computed with the known geometric properties, material properties, and axial force value acting on it. In the second, all or some of the geometric and material properties of a column cross-section capable of bearing the known N-M effects are investigated.

On a thick column cross-section, while moment bearing capacity computations can be completed at once, the design computations may need to be repeated many times. When N-M interaction diagrams are used, the number of design computations that are carried out repeatedly by trial and error method reduce. Although N-M interaction diagrams are very useful for column designs, they have also disadvantages due to reasons such as errors made in the selection or determination of the diagram for design, errors made in data reading, and not always finding of proper interaction diagram for a specific reinforcement arrangement or a specific geometric cross-section.

In this study, an alternative, a novel and powerful artificial intelligence method called Fuzzy Inverse Logic was presented for column design computations. For this purpose, firstly, an FL model was constituted to determine the column moment capacities and the validity of this model was proven. Then, applying the FIL method to this FL model, designs were performed for thick reinforced concrete columns.

FUZZY INVERSE LOGIC (FIL) METHOD

By the FL method developed by inspiring the ability of human beings to make inferences, only forward-looking inferences can be made. In other words, the output(s) is/are tried to be computed or determined by using known net values of the input parameters of a problem by the FL method. Inspired by the ability of human beings to infer backward from time to time, the author developed the FIL method [31, 32], which can infer backward by using the entire infrastructure of the FL method. That is, it is possible determining the values of the input parameters by the FIL method for the desired output in a data range containing the known outputs of a problem. To express the FIL method mathematically, let us assume that *p, r, s,* and *t* are the number of fuzzy sets belonging to *X, Y,* and *Z* input variables and *W* output in an FL model respectively. The value of the *W* output is investigated for the net *a, b,* and *c* numerical values of *X, Y, and Z* input variables (*if X=a Ç Y= b Ç Z= c then W=?*) in the data of this FL model of which general expression is given in Eq. (5). On the contrary, by the FIL method, the net values of the *X, Y* and *Z* input variables are tried to be determined for a desired net output (*W=d*) of the problem. Since the *1D FIL* method is rather a new

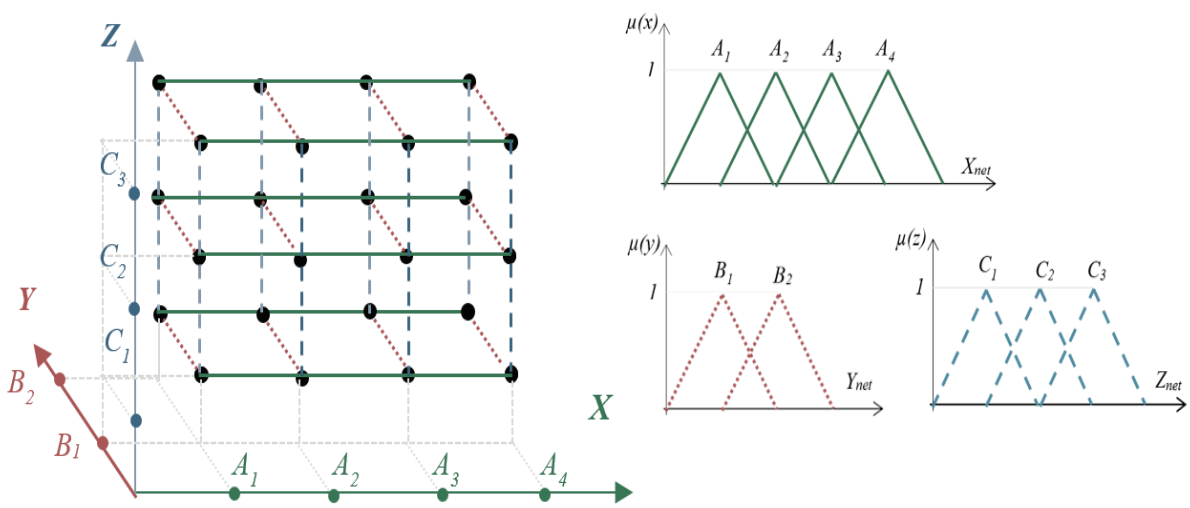

Figure 3. 3D global solution space for X, Y, and Z variables with 4, 2, and 3 fuzzy sets respectively.

method, its working principles and computation details have been tried to be explained more clearly below.

$$X = Ai \cap Y = Bj \cap Z = Ck \text{ then } W = O_m \; (i = 1,2,\dots,p\,;\; j = 1,2,\dots,r\,;\; k = 1,2,..,s;\; m = 1,2,\dots,t) \quad (5)$$

Since the FIL method is completely built on the foundations of the FL method, classifying of fuzzy sets, determination of membership degrees, the constitution of rules with fuzzy propositions, and rule data in the FIL method are exactly the same as those of the FL method. Moreover, the FIL method can be applied directly to current FL models. On the other hand, since the FIL method was developed and tested in such a way that all the condition terms in the fuzzy rules are "*AND (Ç)*" for now, the application of the FIL method on only the FL models all of whose rules constituted with the "*AND (Ç)*" condition term is recommended in this study. However, for the successful use of the FIL method, a very well and precisely constructed FL model is needed and the same fuzzification method used in the FL model must be used in the FIL method.

The rule base constituted by using the inputs and outputs of the solved examples previously is considered as a solution space or an output space in the FIL computations. In a rule base with *n* variable input parameters, the global solution space is n-dimensional *(nD)*. As an example, the *3D* space shown in Figure 3 is the global solution space for a problem having three input variables such as *X, Y,* and *Z*. The black dots in this Figure are known solutions corresponding to the fuzzy outputs obtained with the combined fuzzy input sets A_i, B_j, and C_k *(i=1,2,3,4; j=1,2; k=1,2,3)* of the input parameters *X, Y,* and *Z* in the FL model respectively.

It can be a lot of sub-solution space(s) (sub-output space(s) or solution dimension(s)) in FIL computations depending on the number of input parameters in the problem on which the method is applied. For example, in a problem with *n* input parameters, there are *0D, 1D, 2D, . . , (n-1)D* and *nD* sub-solution spaces.

A *0D* sub-solution space corresponds to an output point (a fuzzy rule of which inputs and output are known) in the *nD* global solution space. That is, if the desired output exists in a *0D* sub-solution space, it can correspond to the output of any of the 2^0=1 rule in the fuzzy rule base. Therefore, the net values of the input parameters in the *0D* sub-solution space are equal to the net values obtained from the inverse fuzzification processes performed on fuzzy sets (the fuzzy inputs of the rules having the desired output) of these parameters for the membership degree 1. The number of the *0D* FIL output(s) is equal to the number of rule(s) of which output(s) correspond(s) to the desired output in the global solution space.

As seen in Figure 3, The *1D* sub-solution spaces are the straight lines drawn in the axes' directions between the 2^1=2 adjacent points where the memberships degrees of all variables except one variable are equal to 1. Mathematically, if the desired output is in a *1D* sub-solution space, it is on a straight line (excluding its endpoints) of which endpoints' coordinates are known. Similarly, a sub-solution space whose dimension is bigger than 1 is constituted by $2_{Dimension}$ adjacent points. For example, in a *d* dimensional sub-solution space *(1<d≤ n)*, a sub-solution space consists of 2_d adjacent output points.

In the FIL computations, as the solution dimension increases, the computational volume increases but the accuracy of the FIL method decreases [32]. Because the 0D solutions correspond to the known and limited FL outputs exactly, it is not sense to perform FIL computations in this dimension. For this reason, the most sensitive and practical computations with the FIL method are the computations that are to be performed in *1D* sub-solution spaces. Although close solutions to the real results can be obtained in *dD* computations *(1<d≤n)* from time to time too, it requires the more sensitive FL models developed by more data to increase the sensitivity and decrease the error levels in these computations.

In a global solution space with definite boundaries, using more data to perform precise FIL computations bigger than 1D increases both sensitivity and the number of 1D sub-solution spaces. This will reduce or eliminates the need for computations bigger than 1D. In addition, it should also be noted here that it is possible to reach a much larger number of solutions in the bigger sub-solutions spaces, However, since the FIL method can produce quite a lot of results in small-dimensional computations, even in 1D computations, there is usually no need for big-dimensional computations in terms of the number of solutions. Considering all the situations described above, the solution dimension was chosen as 1D and therefore only the 1D computation details of the FIL method are presented in this study.

1D Fuzzy Inverse Logic (FIL) method

The solution dimension in FIL computations indicates the numbers of the input parameters taken as variables in the problem. For example, while one of the input parameters is taken as a variable, the other(s) is/are kept constant in 1D FIL computations. Similarly, in the 2D, 3D, and nD FIL computations, while any of 2, 3, and n parameters are taken as variables respectively, the other(s) is/are kept constant.

To reach all 1D FIL solutions in a problem, all computations in each of which a different input parameter is/ taken as a variable must be performed. For a simpler explanation, a global output space for a problem having two input parameters such as *X* and *Y* and an output parameter such as *W* are shown in a plane in Figure 4. It is understood from this figure that *X* and *Y* parameters have ***m*** and ***n*** fuzzy sets respectively. This means that there are ***n*** 1D-output- spaces (sub-solution-spaces) where the Y parameter is variable for each constant A_i input of the *X* parameter*(1≤i≤m)* and there are ***m*** 1D-output-spaces where the *X* parameter is variable for each constant B_j input of the Y parameter *(1≤ j≤ n)*. One of these 1D-output-spaces was shown as shaded in the horizontal direction for the X variable and another one was shown in the vertical direction for the Y variable in Figure 4. In the global output space in Figure 4, each black point corresponds to the rule outputs in the fuzzy model, and the thick black lines between any two adjacent rule outputs (black points) in a 1D-output-space are the parts of this space and are defined as sub-solution-space-parts or output-space-parts in this study.

In the 1D FIL method, computations start by investigating whether the desired O_D output is available in each output-space-part of all 1D-output-spaces. As seen from Figure 5 and Eq. (6), if an O_D value of the desired output is between the values of the rule outputs (O_S and O_B; small and big values of the rule outputs respectively) at the two points defining a 1D-output-space-part, it is understood that a 1D FIL solution exists for O_D in this output-space-part.

$$O_s < O_D < O_B \tag{6}$$

An output-space-part in which O_D output exists is defined as valid-output-space-part or valid-sub-solution-space-part, and the rules containing outputs that define this valid-output-space-part are defined as valid rules in this study.

Determination of valid output-space parts and/or valid rules are the first step of FIL computations. In the second step of FIL computations, valid fuzzy sets of input parameters (fuzzy coordinates of sub-solution spaces) are determined.

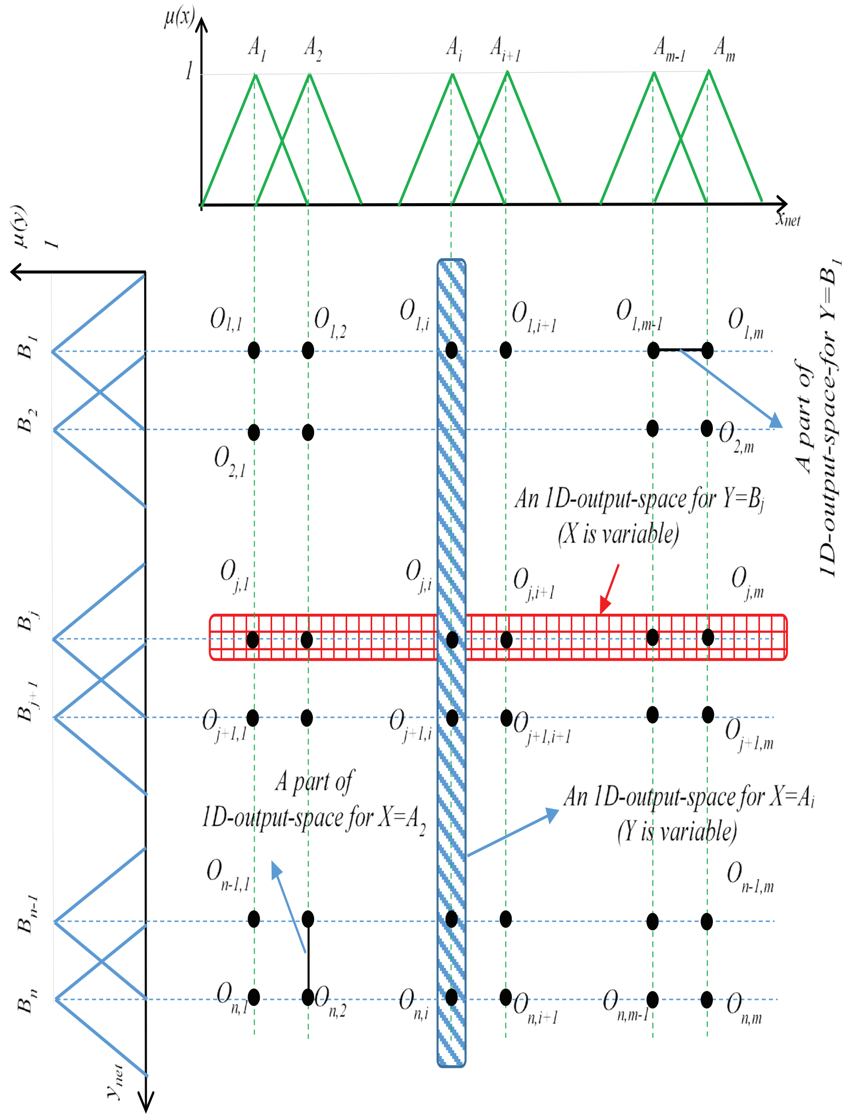

Figure 4. 1D-output-spaces for X and Y variables in the global output space of an FL Model

The fuzzy sets of input parameters constituting the two adjacent valid rules satisfying Eq. (6) are the fuzzy coordinates of a valid 1D-output-space-part. In 1D FIL computations, the fuzzy coordinates of the input parameters of these two valid rules, except the variable parameter, are the same.

The coordinate of a variable parameter in a valid rule is computed by two fuzzy sets, which are adjacent to each other in a valid 1D-output-space-part, of that parameter. These fuzzy sets are called valid fuzzy sets in the FIL method. As an example, the valid fuzzy sets (A_i, A_{i+1}) which are corresponding to the O_S and O_B outputs of the two adjacent valid rules for an X variable parameter are presented in Figure 6. As can be seen from this figure, the 1D FIL method has been developed considering that there is only one O_D value between O_S and O_B. If there is more than 1 O_D value in this range, the accuracy of the 1D FIL method decreases. In this case, the best thing to do is to increase the sensitivity of the FL model on which the 1D FIL method is applied.

In the third step of the FIL method, the memberships of valid fuzzy sets of the variable parameter are computed. Inversely to the FL computations, it is tried to determine the membership degrees of the fuzzy sets belonging to two variable parameters in a 1D-output-space-part (see Figure 7). For this purpose, Eq. (7) is used instead of Eq. (4) in FIL computations. Finally, Eq. (8) and Eq. (9) were written for the computations of the $m(A_i)$ and $m(A_{i+1})$ membership degrees with the help of Eq. (3) and Eq. (7).

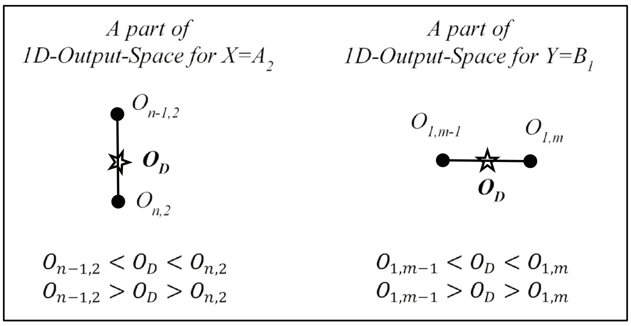

Figure 5. Detection of the desired O_D output in a 1D-output-space-part.

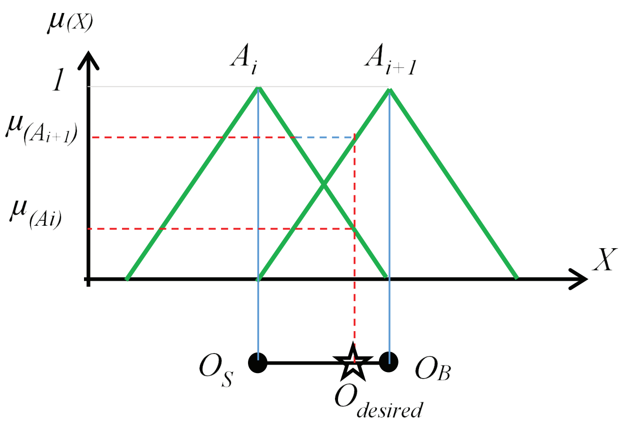

Figure 6. Valid fuzzy sets (A_i, A_{i+1}) for the X variable parameter

$$O_D = O_{j,i}.\mu_{(A_i)} + O_{j,i+1}.\mu_{(A_{i+1})} \quad (7)$$

$$\mu_{(A_i)} = \frac{O_D - O_{j,i+1}}{O_{j,i} - O_{j,i+1}} \quad (8)$$

$$\mu_{(A_{i+1})} = \frac{O_D - O_{j,i}}{O_{j,i+1} - O_{j,i}} \quad (9)$$

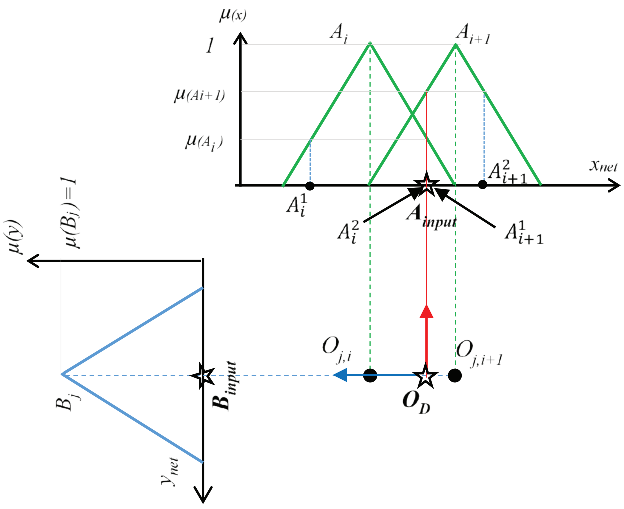

Figure 7. Determination of membership degrees and net input values in the 1D FIL method.

In the last step of the FIL method, the net values of the input parameters are computed. Since there is a fuzzy set with membership degrees equal to 1 for each of the constant input parameters, the net input value of these constant parameters can be easily computed by inverting the fuzzification process. On the other hand, there exist two fuzzy sets belonging to the variable parameter. After membership functions of these sets are equalized to their membership degrees found in the previous step, a net input value that provides this equality is computed (See Eq. (10), Eq. (11), and Eq. (12)).

$$f(x_i) = \mu_{(A_i)} \rightarrow x_i = \begin{cases} {A_i}^1 \\ {A_i}^2 \end{cases} \quad (10)$$

$$f(x_{i+1}) = \mu_{(A_{i+1})} \rightarrow x_{i+1} = \begin{cases} {A_{i+1}}^1 \\ {A_{i+1}}^2 \end{cases} \quad (11)$$

$$X_{net} = {A_i}^2 = {A_{i+1}}^1 \quad (12)$$

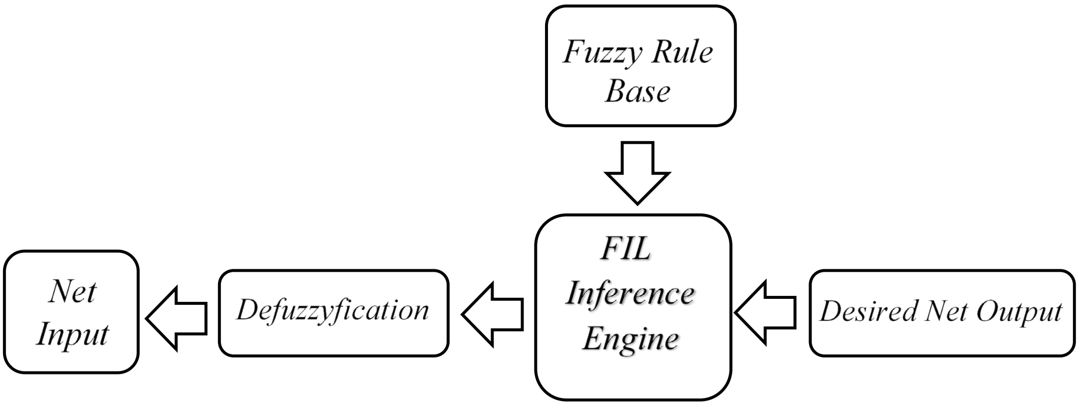

Figure 8. Flowchart of Fuzzy Inverse Logic.

Where A_i^1 and A_i^2 are first and second net values corresponding to A_i valid fuzzy set of X variable and A_{i+1}^1 and A_{i+1}^2 are first and second net values corresponding to A_{i+1} valid fuzzy set of the X variable. All the computation processes to be performed in the 1D FIL method were summarized in Figure 8.

DEVELOPMENT OF AN FL MODEL FOR DETERMINATION OF MOMENT BEARING CAPACITY OF THICK COLUMNS

In the development of a FL model, lateral reinforcement diameter (f_w= 8mm), the characteristic reinforcement strength (f_{ck}=420 MPa), the concrete cover thickness *(c=25 mm),* and the equivalent rectangular stress block parameter (k_1=0.8) are chosen as constant [39]. In addition, while, ultimate concrete strain and Young modulus of reinforcement steel were taken into consideration as e_{cu} =0.003 and $E=2x10^5$ MPa respectively, the distances that must be left between two reinforcement bars, minimum eccentricity value of the axial load, and the minimum and the maximum reinforcement ratios were not taken into consideration during computations of the moment bearing capacities. Cross-section dimensions *(b, h),* longitudinal reinforcement diameter, number of reinforcement rows in the *X* direction (R_x) and in the *Y* direction (R_y) of the section (see Figure 9), characteristic concrete compressive strength (f_{ck}), and an axial force ratio $N_r=N/(b.h.(f_{ck}/1.5))$ were taken as variable input parameters. Finally, in the developed FL model, moment capacity (M_r) was defined as the output parameter. The values of the input parameters used for the development of the FL Model are given in Table 1. As seen from this table and Figure 9, the FL model was developed to perform designs of the symmetrically reinforced thick columns for 3 different section widths *(b)* and 3 different section heights *(h)*, 3 different reinforcement rows in each of *X* and *Y* directions, 4 different reinforcement diameters (f_L), 4 different concrete compressive strengths (f_{ck}) and 12 different axial force ratios (N_r). In structural codes [40, 41], axial load levels were limited in columns for structural ductility. Limitations on the axial load level are made according to the axial load capacity of the column cross sections in the building codes. Therefore, the $N_r=N/(b.h.(f_{ck}/1.5))$ ratio which defines the axial load level in

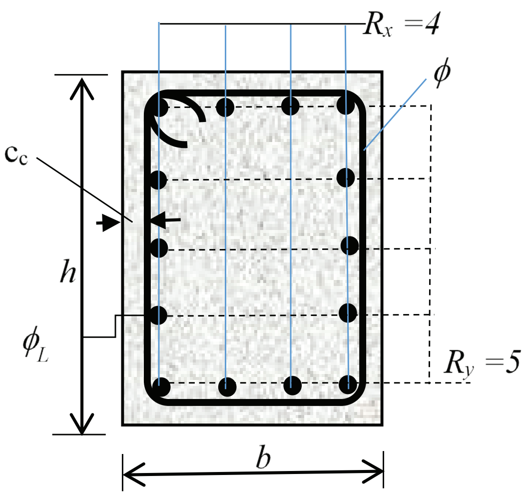

Figure 9. Symmetrically reinforced column cross-section with R_x=4 and R_y=5.

Table 1. Problem variables and their values used in the development of the FL model.

Variables	*Values*
b (mm)	300, 400, 500
h (mm)	300, 400, 500
f_L (mm)	14, 16, 18, 20
Rx (number)	3, 4, 5
Ry (number)	3, 4, 5
fck (MPa)	20, 30, 40, 50
Nr	0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, 0.50, 0.55, 0.60

a column cross-section was used as an input instead of the axial load value of N in this study.

In the development of the FL model, fuzzy sets were constituted by using triangular membership functions for all variable parameters. 3 different fuzzy sets constituted for each of the section width *(b)* and section height *(h)* are shown together in Figure 10. As shown in Figure 11, Figure 12, Figure 13, and Figure 14 respectively, 4 fuzzy sets for the reinforcement diameter, 3 fuzzy sets for the number of reinforcement rows in each the *X* and *Y* directions (R_x, R_y), 4 different sets for the concrete compressive strength(f_{ck}) and 12 fuzzy sets for the N_r ratio were constituted.

In order to constitute fuzzy sets belonging to the output parameter of M_r. conventional moment capacity computations on reinforced concrete thick columns were carried out for the whole (15552) combinations of the values of the input parameters. For this, a computer code was written in the Visual Basic programming language [42]. At the end of conventional moment capacity computations, the obtained results were converted to the nearest integer values and so 573 different moment capacity values in the range of 58 *kNm* and 705 *kNm* values were obtained. Using all these M_r values, 573 fuzzy output sets were constituted by triangular membership functions. However, due to a large number of these sets, they could not be shown in the figures in this study.

One of the most another important point in the development of a fuzzy logic model is the constitution of the rule table. If it is possible, the rule table is prepared for the total number of combinations of input parameters. For this reason, 15552 rules were constituted by Eq. 13 for the rule table in this study. As seen from this equation "*AND*" condition term was used in all of the rules in this study.

$$\textbf{\textit{if}}\ b = \{b\}_i\ \textbf{\textit{and}}\ h = \{h\}_j\ \textbf{\textit{and}}\ \emptyset_L = \{\emptyset_L\}_k\ \textbf{\textit{and}}\ R_x = \{R_x\}_l\ \textbf{\textit{and}}\ R_y = \{R_y\}_m\ \textbf{\textit{and}}\ f_{ck} = \{f_{ck}\}_n\ \textbf{\textit{and}}\ N_r = \{N_r\}_p\ \textbf{\textit{then}}\ M_r = \{M_r\}_r \quad (13)$$

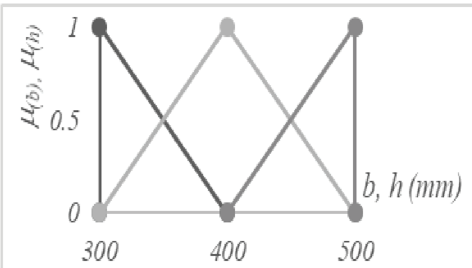

Figure 10. Fuzzy sets with triangular membership functions for section width (b) and section height (h).

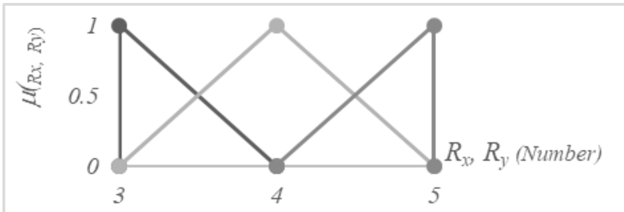

Figure 12. Fuzzy sets with triangular membership functions for the reinforcement rows in the *X* and *Y* directions (R_x and R_y).

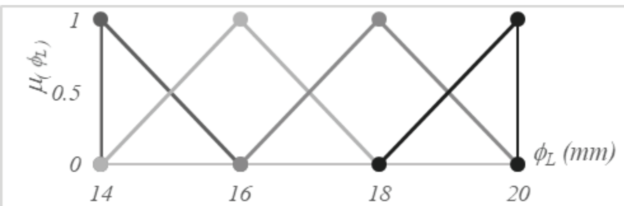

Figure 11. Fuzzy sets with triangular membership functions for reinforcement diameter ϕ_L.

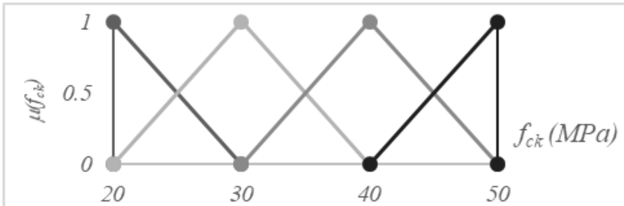

Figure 13. Fuzzy sets with triangular membership functions for the concrete compressive strength (f_{ck}).

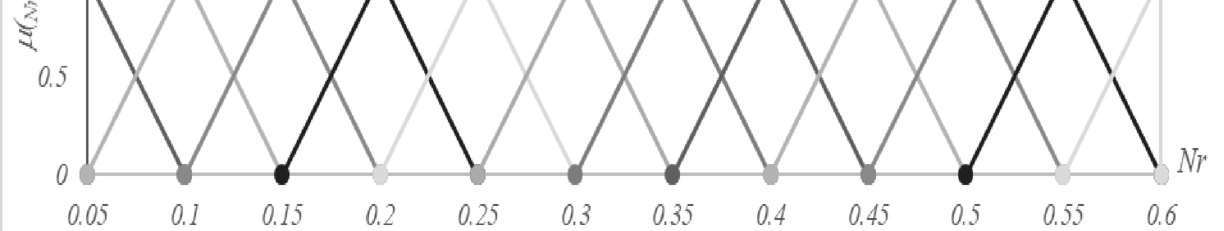

Figure 14. Fuzzy sets with triangular membership functions for the axial force ratio of N_r.

In Eq. 13, $\{b\}_i$, $\{h\}_j$, $\{f_L\}_k$, $\{R_x\}_l$, $\{R_y\}_m$, $\{f_{ck}\}_n$, $\{N_r\}_p$ and $\{M_r\}_r$; represent the fuzzy sets with numbers *i, j, k, l, m, n, p* and *r* belonging to the *b, h,* f_L, R_x, R_y, f_{ck}, N_r input variables and to the M_r output respectively.

Testing of the Developed FL model

To validate the developed FL model, it was tested by using the values given in Table 2 other than the net input values of the problem parameters (excluding f_L, R_x, *and* R_y). As can be seen from this table, 4752 different combinations were constituted using 2 different net input values for each of the *b* and *h* parameters, 3 different input values for the f_{ck} parameter, and 11 different input values for the N_r parameter. Since there are no reinforcement diameters between 14mm and 20mm diameters in the market except *f*14, *f*16, *f*18, and *f*20 and it is not possible to use other integer reinforcement rows other than 3, 4, and 5 between the value ranges of 3 and 5, the same net values used during model development of the FL model for the parameters of f_L, R_x and R_y were also used in the validation phase of the FL model.

In the technical literature, there is a common view that the number of validation data should be at least 10% of the number of data used in the development of a model. In this study, the validation data is more than 30% of the data used to develop the FL model. This is an indication that the number of validation data is sufficient in this study.

Moment bearing capacities of thick columns were obtained by using both the conventional reinforced concrete computation method and the FL model developed in this study for 4752 validation data. In order to evaluate the accuracy of the developed FL model, conventional computation results and FL model outputs were compared. In Figure 15, it is seen that the outputs of the FL model are quite close to the results obtained by conventional reinforced concrete computation. The correlation coefficient computed as R^2=0.9998 between FL outputs and the conventional computation results shows the good agreement between the FL outputs and the results obtained by conventional computations.

Table 2. Variable values used in the validation of the developed FL model

Variables	*Values*
b *(mm)*	*350, 450*
h *(mm)*	*350,450*
fL *(mm)*	*14, 16, 18, 20*
Rx	*3, 4, 5*
Ry	*3, 4, 5*
fck *(MPa)*	*25, 35, 45*
Nr	*0.075, 0.125, 0.175, 0.225, 0.275, 0.325, 0.375, 0.425, 0.475, 0.525, 0.575*

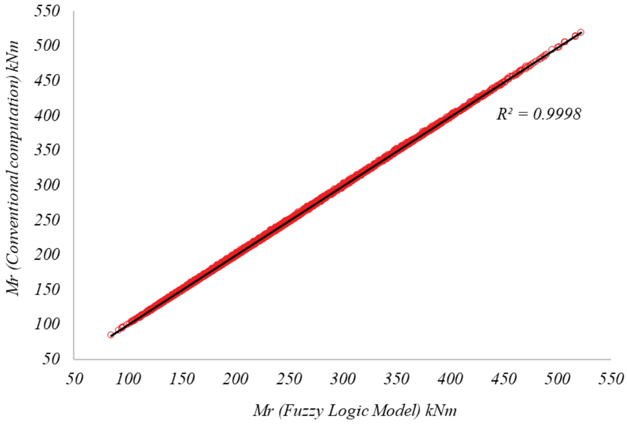

Figure 15. The correlation between FL outputs and the results of conventional computations.

In order to demonstrate the validity of the FL model developed in this study, Percentage Error (PE), Mean Absolute Percentage Error (MAPE), Relative Root Mean Squared Error (RMSE), Relative Root Mean Squared Error (RRMSE), and Performance Index (PI) computations were performed between the results of conventional computations and the FL outputs by the Eq. (14), Eq. (15), Eq. (16), Eq. (17) and Eq. (18) respectively. As a result of validation computations, while, maximum percentage error(PE_{max}), minimum percentage error (PE_{min}) and mean percentage error (PE_{mean}) were obtained as 1.599%, -0.996%, and 0.642% respectively, MAPE, RMSE, RRMSE, PI were obtained as 0.676, 1.849, 0.0074, 0.0037 respectively.

$$PE = \frac{Mr^{FL} - Mr^{CC}}{Mr^{CC}} \times 100 \tag{14}$$

$$MAPE = \frac{100}{n}\sum_{i=1}^{n}\frac{\left|Mr_i^{CC} - Mr_i^{FL}\right|}{\left|Mr_i^{CC}\right|} \tag{15}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Mr_i^{CC} - Mr_i^{FL})^2}{n}} \tag{16}$$

$$RRMSE = \frac{1}{\left|\overline{Mr_i^{CC}}\right|}\sqrt{\frac{\sum_{i=1}^{n}(Mr_i^{CC} - Mr_i^{FL})^2}{n}} \tag{17}$$

$$PI = \frac{RRMSE}{1+R} \tag{18}$$

Table 3. Unknown problem parameters and the values of known parameters in the 15 different column

Problem ID	*b (mm)*	*h (mm)*	f_L *(mm)*	R_x	R_x	f_{ck} *(MPa)*	N_r	M_r *(kNm)*
P-1	?	?	?	?	?	?	?	245
P-2	300	400	18	?	?	35	0.45	271
P-3	400	500	?	?	?	?	0.4	300
P-4	400	450	?	?	?	30	0.375	350
P-5	300	350	16	4	3	20	?	111.5
P-6	?	?	14	3	4	?	0.15	203
P-7	300	300	?	?	?	45	?	185
P-8	?	?	?	?	?	?	0.25	655
P-9	450	450	20	5	3	?	0.35	511
P-10	?	?	?	?	?	50	0.2	450
P-11	350	?	16	?	3	?	0.5	181
P-12	400	?	?	?	?	?	0.55	400
P-13	?	500	20	5	5	?	0.33	675
P-14	?	300	20	3	3	?	0.20	111
P-15	?	300	20	3	3	35	0.20	110

Considering the general assumptions made for reinforced concrete computations, it can be easily said that the errors given above are within acceptable limits. In other words, correlation coefficient and % error computations demonstrate that the FL model developed for M_r computation produces quite good outputs and can be used in the determination of the moment bearing capacity of thick columns.

Design of Columns by Fil Method (Application of the Fil Method to the Developed Fl Model)

First, it should be noted here again that the results obtained by the FIL method cannot be outside of the data ranges (global solution space) used in the development of the FL model. To show the efficiency and capability of the 1D FIL method, it was applied to the developed FL model by a program code written in the Visual Basic language [42] within the scope of this study for 15 different thick column problems given in Table 3. In each of the 1D FIL computations, alternative designs were investigated by taking only one of the unknown input parameters as a variable.

As can be seen from Table 3, thick column designs were investigated for different desired M_r moment values and known numerical values of some of the input parameters in each of the 15 problems. Other input parameters shown with a question mark in the gray shaded areas in Table 3 are the design parameters of which values were investigated to determine the designs.

RESULTS AND DISCUSSION

As a result of the 1D FIL computations performed separately for each of these problems given in Table 3, a total of 9737 designs were obtained. Since it is not possible to present all of these designs here, all designs, for P_2, P_5, P_8, P_9, P_{13}, $P_{14,}$ and P_{15} problems with design numbers less than 10 and 10 sample designs for the P_1, P_3, P_4, P_6, P_7, P_{10}, P_{11} and P_{12} problems with more than 10 design numbers are presented in Table 4.

Since the 1st problem is a general problem and it has the most outputs, evaluations about it were made in detail below. Considering the other problems together with the 1st problem, brief and general evaluations were made about the 1D FIL method. On the other hand, the large number of sample problems did not make them possible to examine separately and in detail.

In problem-1, it is investigated the solutions to a general question such as "For which values of axial force and design parameters a column bears a moment of 245 kNm?". In other words, only the value of the moment acting on this column is known *(M_r=245 kNm)* and the values of other parameters were investigated for this question.

A designer may not be confronted directly with such a question. However, a researcher may want to investigate the answer(s) to this question. Indeed, there may be many possible alternative answers to this question. However, if computations are to be made with conventional methods, it is necessary to decide in advance how to start the computations. Because even for a single answer, computations with a high volume are needed in these conventional methods in which the trial and error method is used.

When the 1D FIL method was applied to the developed fuzzy model for this problem, 9323 outputs were obtained. In addition to all of these 9323 FIL outputs which were different from each other, there were also 54 rules in the FL model that directly give the output of M_r*=245 kNm.*

Table 4. Some column designs obtained for Problems 1-15 by the 1D FIL method

Prb. ID	M_r *(kNm)*	*S. No*	*b (mm)*	*h (mm)*	f_L *(mm)*	R_x	R_x	f_{ck} *(MPa)*	N_r	*S. No*	*b (mm)*	*h (mm)*	f_L *(mm)*	R_x	R_x	f_{ck} *(MPa)*	N_r
P-1	**245**	*1*	300	396.97	14	4	5	50	0.35	*6*	400	458.02	18	4	3	20	0.25
	245	*2*	300	397.78	16	5	5	40	0.2	*7*	400	400	18	4	4	43.33	0.1
	245	*3*	300	381.82	18	4	5	40	0.25	*8*	400	400	18	4	5	48.46	0.05
	245	*4*	300	338.84	18	5	4	50	0.35	*9*	400	400	18	5	4	29.58	0.1
	245	*5*	300	385.86	20	3	5	40	0.25	*10*	400	400	18	5	5	22.96	0.1
P-2	**271**	*1*	**300**	**400**	**18**	4.84	5	**35**	**0.45**	*2*	**300**	**400**	**18**	5	4.63	**35**	**0.45**
P-3	**300**	*1*	**400**	**500**	15.81	3	3	30	**0.4**	*6*	**400**	**500**	16	4	4	24.08	**0.4**
	300	*2*	**400**	**500**	14	3.79	3	30	**0.4**	*7*	**400**	**500**	17	4	5	20	**0.4**
	300	*3*	**400**	**500**	14	3	3	32.7130	**0.4**	*8*	**400**	**500**	16	4.6	5	20	**0.4**
	300	*4*	**400**	**500**	15.043	3	4	30	**0.4**	*9*	**400**	**500**	16	4	5	22.57	**0.4**
	300	*5*	**400**	**500**	14	3.5	4		**0.4**	*10*	**400**	**500**	16.3	5	3	20	**0.4**
P4	**350**	*1*	**400**	**450**	17.414	5	5	30	**0.375**	*6*	**400**	**450**	18	5	4.021	30	**0.375**
	350	*2*	**400**	**450**	19.259	4	5	30	**0.375**	*7*	**400**	**450**	20	3.685	5	30	**0.375**
	350	*3*	**400**	**450**	18	4.66	5	30	**0.375**	*8*	**400**	**450**	20	4.315	3	30	**0.375**
	350	*4*	**400**	**450**	18.526	5	3	30	**0.375**	*9*	**400**	**450**	20	4.024	4	30	**0.375**
	350	*5*	**400**	**450**	18.012	5	4	30	**0.375**	*10*	**400**	**450**	20	4	4.070	30	**0.375**
P5	**111.5**	*1*	**300**	**350**	16	4	3	20	0.067	-	-	-	-	-	-	-	-
P6	**203**	*1*	300	470.58	**14**	**3**	**4**	40	**0.15**	*6*	400	424.096	**14**	**3**	**4**	40	**0.15**
	203	*2*	379.41	400	**14**	**3**	**4**	50	**0.15**	*7*	400	400	**14**	**3**	**4**	47.407	**0.15**
	203	*3*	300	434.18	**14**	**3**	**4**	50	**0.15**	*8*	400	500	**14**	**3**	**4**	25.349	**0.15**
	203	*4*	337.50	500	**14**	**3**	**4**	30	**0.15**	*9*	500	391.463	**14**	**3**	**4**	40	**0.15**
	203	*5*	300	500	**14**	**3**	**4**	33.75	**0.15**	*10*	500	357.732	**14**	**3**	**4**	50	**0.15**
P7	**185**	*1*	**300**	**300**	17.86	5	4	**45**	0.3	*6*	**300**	**300**	18	5	5	**45**	0.165
	185	*2*	**300**	**300**	17.667	5	4	**45**	0.35	*7*	**300**	**300**	18	5	5	**45**	0.485
	185	*3*	**300**	**300**	17.81	5	4	**45**	0.4	*8*	**300**	**300**	18.128	5	5	**45**	0.5
	185	*4*	**300**	**300**	17.714	5	5	**45**	0.2	*9*	**300**	**300**	18.596	5	5	**45**	0.55
	185	*5*	**300**	**300**	17.375	5	5	**45**	0.25	*10*	**300**	**300**	19.087	5	5	**45**	0.6
P8	**655**	*1*	493.24	500	20	5	5	50	**0.25**	*4*	500	500	20	4.893	5	50	**0.25**
	655	*2*	500	497.53	20	5	5	50	**0.25**	*5*	500	500	20	5	4.737	50	**0.25**
	655	*3*	500	500	19.816	5	5	50	**0.25**	*6*	500	500	20	5	5	49.32	**0.25**
P9	**511**	*1*	450	450	20	5	3	47.85	**0.35**	-	-	-	-	-	-	-	-
P10	**450**	*1*	300	483.824	20	5	4	**50**	**0.2**	*6*	404.69	500	18	4	4	**50**	**0.2**
	450	*2*	300	469.930	20	5	5	**50**	**0.2**	*7*	400	500	18.14	4	4	**50**	**0.2**
	450	*3*	392.42	500	16	5	5	**50**	**0.2**	*8*	400	500	18	4.079	4	**50**	**0.2**
	450	*4*	375.76	500	18	4	5	**50**	**0.2**	*9*	400	500	18	4	4.158	**50**	**0.2**
	450	*5*	372.31	500	18	5	3	**50**	**0.2**	*10*	445.45	500	20	3	3	**50**	**0.2**
P11	**181**	*1*	**350**	363.584	**16**	3	**3**	40	**0.5**	*6*	**350**	468.800	**16**	3	**3**	20	**0.5**
	181	*2*	**350**	333.010	**16**	3	**3**	50	**0.5**	*7*	**350**	407.186	**16**	3	**3**	30	**0.5**
	181	*3*	**350**	381.579	**16**	4	**3**	30	**0.5**	*8*	**350**	400	**16**	3.3	**3**	30	**0.5**
	181	*4*	**350**	344.865	**16**	4	**3**	40	**0.5**	*9*	**350**	400	**16**	4	**3**	31.60	**0.5**
	181	*5*	**350**	319.266	**16**	4	**3**	50	**0.5**	*10*	**350**	431.884	**16**	4	**3**	20	**0.5**
P12	**400**	*1*	**400**	499.265	14	3	**5**	50	**0.55**	*6*	**400**	500	14	4	5	46.923	**0.55**
	400	*2*	**400**	493.431	14	4	**4**	50	**0.55**	*7*	**400**	500	14	5	3	47.031	**0.55**
	400	*3*	**400**	485.816	14	4	**5**	50	**0.55**	*8*	**400**	500	14	5	4	45.625	**0.55**
	400	*4*	**400**	486.331	14	5	**3**	50	**0.55**	*9*	**400**	500	15.444	5	5	40	**0.55**
	400	*5*	**400**	480.282	14	5	**4**	50	**0.55**	*10*	**400**	500	14	5	5	44.063	**0.55**
P13	**675**	*1*	480.450	**200**	**20**	**5**	**5**	50	**0.33**	*2*	500	**200**	**20**	**5**	**5**	48.045	**0.33**
P14	**111**	*1*	**340**	300	**20**	**3**	**3**	20	**0.20**	*2*	300	**300**	**20**	**3**	**3**	22.5	**0.20**
P15	**110**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

The outputs of these 54 rules were not included in the 1D FIL outputs and are the points that constitute the output space of the FL model. These 54 fuzzy outputs are defined as 0D outputs in the FIL method. Considering all 1D and 0D outputs, the FL model includes a total of 9377 designs for only a moment of M_r=*245 kNm*. Even only, this result by itself reveals the effectiveness of the FIL method. In the FIL method, it is possible to produce much more designs in dimensions greater than 1D *(nD, n>1)*. However, as mentioned before, as the dimension of the computations increases, the amount of error of outputs also increases.

When 9323 1D FIL designs are examined in detail, it is understood that 8097 of these designs can be used directly without any further processing. The remaining 1226 designs obtained mathematically in the FIL computations, cannot be used directly in practice. Because, in these designs, the number of reinforcement rows R_x and R_y in the *X* and *Y* directions respectively were not obtained as integers. To demonstrate the accuracy and precision of the column designs obtained by the 1D FIL method comparatively, the moment bearing capacities of the directly usable 8097 1D FIL designs were determined conventionally by a computer code written in this scope of this study, and then *PE, MAPE, RMSE,* and *RRMSE* belong to these designs were obtained by Eq. 14, Eq. 15, Eq. 16 and Eq. 17. Finally, while the maximum, the minimum and mean percentage errors were obtained as PE_{max} =*1.063*, PE_{min} = *-1.780* and PE_{mean}= *-0.3162, MAPE, RMSE,* and *RRMSE* were obtained as 0.3733, 1.2903 and 0.0053 for the moment bearing capacities (M_r) of these column designs in this problem respectively.

On the other hand, since the reinforcement rows (R_x and R_y) were not obtained as integers in 1226 1D FIL designs, computations for the accuracy and precision of these designs cannot be possible directly. It is obvious that by rounding up the R_x and R_y values to integer values, 1226 non-applicable FIL designs can be able to turn into applicable designs with a moment capacity greater than but close to desired moment capacity of 245 kNm. When the values of R_x and R_y were converted into integers by rounding up, while PE_{max}, PE_{min}, and PE_{mean} were obtained as 18.022%, -1.780%, and 0.401%, *MAPE, RMSE,* and *RRMSE* were obtained as 0.9137, 5.4699, 0.0223 for all 9323 FIL designs respectively. Here, the main reason for the excessive errors is rounding up. The proof of this is that while PE_{max} increased to 18.022%, PE_{min} remained constant and PE_{mean} increased very little.

In Table 4, the values given with bolded numbers in a row are the exact/known values for which a design was obtained. The others are the values of the parameters that can be taken as variables in the FIL designs. Finally, the number given in a shaded area for a design is the value of the variable parameter of that design. There is only a shaded area (a variable parameter) in each FIL design.

1D FIL method cannot produce any design for some known values of the problem parameters. As an example, the known values given in Table 3 for Problem 15 can be shown. In this problem except for the f_{ck} parameter and M_r output, the values of other parameters were the same as those of Problem 14. Although, two designs with f_{ck}=*20 MPa* and f_{ck}=*22.5 MPa* could be obtained for M_r=*111 kNm* in Problem 14, no design produced with f_{ck}=*35 MPa* for M_r=*110 kNm*. This means that, although it may be possible to produce designs that can bear smaller or bigger moment values than M_r=*110kNm* for the data of Problem 15, it was not possible to produce any design to bear an exact moment value of M_r=*110kNm* with the same data. Another meaning of this is that the 1D FIL method produces only optimum designs for the *Demand/Capacity=1*.

When Table 4 is also carefully examined for Problem 2-Problem14, it is understood that although some designs obtained can be used directly, other designs cannot be used directly as in Problem 1. The reason for this is that the R_x and R_y numbers in these designs determined by the 1D FIL method cannot be obtained as integers like in Problem-1. This is a common situation encountered in conventional reinforced concrete designs and such designs turn applicable by converting the non-integer reinforcement number into the nearest upper integer number. It is possible to perform the same procedure for 1D FIL designs. However, although the designs are made applicable by performing this rounding up process, the amount of error in these designs increases while obtaining safer designs. For these reasons, error computations were performed on two different design data for all other problems as in Problem-1 to demonstrate the accuracy and precision of the designs obtained by the 1D FIL method. The first of them is the data of designs that can be applied directly to eliminate the errors caused by rounding. The second type of design data includes both the designs obtained after the rounding process and the designs that can be applied directly. After these percentage errors were determined for each problem, the PE_{max}, PE_{min} and PE_{mean}, *MAPE, RMSE,* and *RRMSE* were also determined and given in Table 5 for all Problems.

As seen in Table 5, a total of 9737 designs were obtained from 1D FIL computations for only 15 column design problems. When the percent errors of the designs that can be used directly are examined in Table 5, while the maximum of PE_{max} and the minimum of PE_{min} occurred in the 1st problem with the values of 1.063% and -1,780% respectively, the maximum and the minimum of PE_{mean} detected as 0.191% and -0.692% in the 5th and the 11th problems respectively. However, while maximum values of MAPE, RMSE, and RRMSE were determined as 0.692, 1.901, and 0.0084 respectively, minimum values of them were obtained as 0.021, 0.114, and 0.003 respectively. The error values in these directly applicable designs obtained by the 1D FIL method are the most obvious results that are one of the proofs of capability and effectiveness of the method.

In the designs that require rounding in reinforcement rows, after rounding up while the maximum of PE_{max} and the minimum of PE_{min} occurred in the 1st problem with

Table 5. The number of designs obtained by the 1D FIL method for 15 different problems and the error values computed for these designs

Problem ID	Errors for the designs that can be used directly							Errors for all designs after rounding up						
	Number of designs	PE_{min}	PE_{max}	PE_{mean}	MAPE	RMSE	RRMSE	Number of designs	PE_{min}	PE_{max}	PE_{mean}	MAPE	RMSE	RRMSE
P-1	8097	-1.780	1.063	-0.316	0.370	1.289	0.0053	9323	-1.780	18.022	0.401	0.998	5.704	0.023
P-2	0	-	-	-	-	-	-	2	1.449	1.449	1.449	1.449	3.927	0.014
P-3	32	-0.198	0.105	-0.027	0.069	0.257	0.0009	45	-0.198	14.231	1.454	1.522	10.646	0.035
P-4	4	-0.666	-0.299	-0.523	0.523	1.901	0.005	10	-0.666	11.070	2.887	3.305	16.512	0.046
P-5	1	0.191	0.191	0.191	0.191	0.213	0.0019	1	0.191	0.191	0.191	0.191	0.213	0.0019
P-6	16	-1.340	0.133	-0.315	0.342	1.010	0.005	16	-1.340	0.133	-0.315	0.342	1.010	0.005
P-7	52	-0.299	0.218	-0.077	0.256	0.114	0.0014	109	-0.299	12.449	2.243	2.334	7.413	0.0392
P-8	4	-0.051	-0.005	-0.021	0.021	0.178	0.0003	6	-0.051	0.787	0.249	0.276	2.981	0.0045
P-9	1	-0.640	-0.640	-0.640	0.640	0.372	0.0064	1	-0.640	-0.640	-0.640	0.640	0.372	0.0064
P-10	83	-0.762	0.094	-0.240	0.255	1.587	0.0035	101	-0.762	9.507	0.424	0.831	5.589	0.0190
P-11	15	-1.451	-0.029	-0.692	0.692	1.516	0.0084	16	-1.451	-0.029	-0.663	0.663	1.471	0.0082
P-12	89	-0.811	0.130	-0.293	0.300	1.680	0.0042	103	-0.811	9.153	0.247	0.771	6.864	0.0171
P-13	2	0.138	0.138	0.138	0.138	0.929	0.0014	2	0.138	0.138	0.138	0.138	0.929	0.0014
P-14	2	0.042	0.277	0.16	0.220	0.260	0.0020	2	0.042	0.277	0.16	0.220	0.260	0.0020
P-15	0	-	-	-	-	-	-	0	-	-	-	-	-	-
Maximum		0.191	1.063	0.191	0.692	1.901	0.0084	Maximum	1.449	18.022	2.887	3.305	16.512	0.046
Minimum		-1.780	-0.640	-0.692	0.021	0.114	0.0003	Minimum	-1.780	-0.640	-0.663	0.138	0.213	0.014

values of % 18.022 and % -1.780, the maximum and the minimum values of PE_{mean} were obtained in the 4th and 11th problems as 2.887% and -0.663% respectively. However, while maximum values of MAPE, RMSE, and RRMSE were determined as 3.305, 16.512, and 0.0046 respectively, minimum values of them were obtained as 0.138, 0.213, and 0.014 respectively. By using the same fuzzy model (Same membership functions, same rule base, same defuzzification method, same variables, etc.) in FIL computations as in FL computations, the same outcomes with the same errors can be obtained for thick column designs presented in this study.

The high number of alternative designs obtained by the 1D FIL method in some problems raises the question of how the design selection will be made. If there are no architectural, economic, aesthetic, constructive, etc. restrictions for the implementation of the design, any of the alternative designs can be used directly and simple sorting techniques that can be performed with the help of a computer can help in this selection. In addition, in the 1D FIL method, some variable parameters of the problem can be kept constant by considering architectural, economic, constructive aesthetics, etc. Thus, by reducing the number of alternative designs, the design selection can be made easily by the designer among a smaller number of alternative designs.

CONCLUSION

The general conclusions obtained from this study were summarized below.

- In this study, the ability to make backward inferences of the FL method by using the FIL Method has been successfully demonstrated.
- A FL model contains data not only to make forward inferences but also to make backward inferences. In the other words, there is no need for extra data or a data operation to apply the FIL method on previously developed sensitive FL models.
- As the number of investigated input parameters increases, the number of results obtained with the 1D FIL method increase.
- The 1D FIL method produces results for only exact values of desired outputs. In the other words, the 1D FIL method produces only optimum results for the ratio of *Demand/Capacity=1*.

In this study, the conclusions that can also be drawn from the column designs with the 1D FIL method are as follows.

- By the 1D FIL method, column designs were successfully performed without using any N-M interaction diagrams.

- It has been observed in the column designs performed in this study that the error level of the 1D FIL method is quite low and the rounding operations lead to safer designs with bigger errors
- By expanding the data used in this study, an artificial intelligence designer can be constituted for whole design procedures of reinforced concrete columns.

Although the 1D FIL method was successfully applied to 15 different column design problems in the field of Civil Engineering in the current study and it produces promising results, it is necessary to test the capability and the effectiveness of this method by applying it to many problems such as control, optimization, design, etc. It should be also searched whether it can be used widely in other scientific disciplines.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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