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Neuro-fuzzy optimisation to model the phenomenon of failure by punching of a slab-column connection without shear reinforcement

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Abstract. Two new predictive design methods are presented in this study. The first is a hybrid method, called neuro-fuzzy, based on neural networks with fuzzy learning. A total of 280 experimental datasets obtained from the literature concerning concentric punching shear tests of reinforced concrete slab-column connections without shear reinforcement were used to test the model (194 for experimentation and 86 for validation) and were endorsed by statistical validation criteria. The punching shear strength predicted by the neuro-fuzzy model was compared with those predicted by current models of punching shear, widely used in the design practice, such as ACI 318-08, SIA262 and CBA93. The neuro-fuzzy model showed high predictive accuracy of resistance to punching according to all of the relevant codes. A second, more user-friendly design method is presented based on a predictive linear regression model that supports all the geometric and material parameters involved in predicting punching shear. Despite its simplicity, this formulation showed accuracy equivalent to that of the neuro-fuzzy model.

Keywords: punching shear strength; slab-column connection; neuro-fuzzy system; size effect; linear regression; meta-heuristics method

1. Introduction

The first instances of flat plate construction occurred early in the last century in France, the United States, and Switzerland, and it was used more commonly in Europe during the 1960s due to its simplicity and economy**.**

Flat plates consist of slabs directly supported on columns without beams. Because of this simplicity, flat plate systems have various economic and functional advantages over other floor systems.

From a structural mechanics viewpoint, however, flat plates are complex structures. Moreover,

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flat plates usually fail in a brittle manner by punching at the slab-column connections within the discontinuity region. Three-dimensional stress patterns develop at these connections due to a combination of high shear and normal stresses, creating a stress state that is complex to analyse accurately. Investigations have been conducted to study this complex phenomenon of concentric punching shear in reinforced-concrete flat plates by trying to estimate the strength of shear failure using mechanical or purely empirical models. In empirical models, punching shear strength was defined considering the flexural capacity of reinforced concrete slabs. This was based on the experimental observation that punching shear strength was similar to the flexural capacities of concrete slabs. Yitzhaki (1966), Long and Rankin (1979). Other studies Pralong (1981) and Nielsen (2000) derived lower bound and upper bound values for punching shear strength based on the theory of plasticity. These formulations did not consider the effect of flexural reinforcement on punching shear strength. Punching shear resistance in mechanical models was determined by some authors using failure criteria based on the experimental observation of shear cracks. In these models, the failure criteria were defined by the inclined radial compressive stress and the tangential compressive strain at the shear crack Kinnunen and Nylender (1960). Bažant and Cao (1987) developed a punching shear strength model considering the size effect of concrete based on principles of fracture mechanics. The size-effect model explained the experimental observations of decreasing punching shear stresses in unreinforced slab-column connections with increasing slab thickness.

Despite the importance of these models to understand the mechanism of failure by punching, the complexity of their use is not justified by their precision. To compensate for this problem, most design codes developed simple equations in which a nominal shear stress is calculated on a section critical to some distance from the column Fig. 1 and compared to a known value. The classical empirical techniques used by many design codes show limited accuracy, so a more robust empirical modelling technique is needed that can resolve the uncertainties encountered in determining punching shear failure mechanisms. Some authors have used predictive modelling to predict the effort of punching shear resistance based on fuzzy learning. Choi *et al.* (2007), and others used neural networks (ANN) Elshafey *et al.* (2011), to achieve the same goal.

This study introduces a new approach for predicting the punching shear strength of concentrically loaded interior slab-column connections using a hybrid method called the neuro-adaptive model. The proposed approach incorporates the concept of critical contours and various geometric and material parameters.

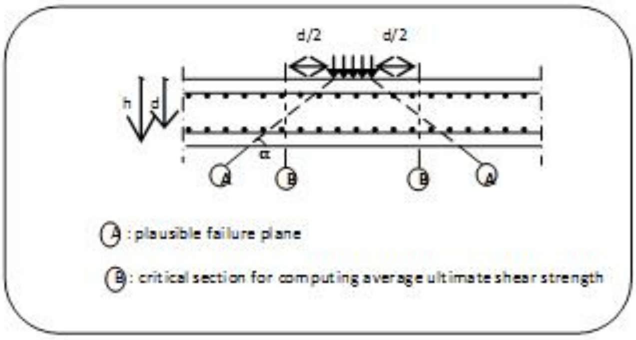

Fig. 1 Cross section of slab-column connection showing critical section at distance d/2 from column face to intersect most plausible failure planes (angle a ranges between 30 and 45 degrees)

2. Literature review

Fuzzy systems and artificial neural networks have been widely used in the last decade for modelling complex engineering systems. Their capability to model complex systems is attributed to their inherent ability to accommodate a tolerance for uncertainty in the modelling parameters. While probabilistic empirical models are limited to considering only random uncertainties, these systems have the ability to consider random and non-random types of uncertainties that arise due to vagueness and/or ambiguity in the modelling parameters and process. Structurally, authors have used neural networks (ANN) to study mechanical problems and quantitative and qualitative building improvements Goh (2004), Ziemianski (2001), Hadim (2003), Lovrovich (1990), Abdalla (2005), Caglar (2008), Kawamura *et al.* (2003). Others applied this method to more specific problems, such as the prediction of beam shear strength with and without reinforcement Sanad *et al*. (2001), Mohamedzein *et al*. (2003), El-Chabib *et al*. (2005), CEB-FIP (1990), Mansour (2004) Goh (1995), the effect of beam size on shear strength Oreta *et al*. (2004), Adhikary (2004), and the study of column shear Caglar (2009). Researchers also found a use for these methods to study local phenomena such as the prediction of shear and anchor at edges Alqedra (2005), the bond between ribbed steel bars and concrete Dahou *et al*. (2009), and prediction of the ultimate moment of beams Pendharkar *et al*. (2007) or reinforced concrete slabs under high temperatures Erdem (2010). Choi *et al*. (2007) proposed an alternative approach to predict the ultimate rupture load by punching in slab-column connections using fuzzy logic, while Bhatt and Agar Bhatt *et al*. (2000) and Elshafey *et al*. (2011) used neural networks to solve the same problem, which was later addressed in several codes around the world.

3.Models used by standard codes

In codes and standards, the nominal shear stress caused by gravity loads is determined at an assumed vertical critical section around the column and, generally, compared to the resistance determined empirically based on several parameters: Yield strength of reinforcement $\mathbf{F_s}$, slab thickness **h**, flexural reinforcement ratio, slab span **L** and compressive strength of concrete $\mathbf{F_c}$. These methods are not very closely related to behaviour of punching in reality, but have the advantage of being simple. If calibrated correctly, reasonable results can be obtained for ordinary cases. (The main differences in results come from the choice of critical perimeter **U** and concrete compressive strength $\mathbf{F_c}$**).** The codes also differ in the choice of parameters that affect the connection punching strength. Marzouk and Hussein (1991), Gardner (1990) and Muttoni (1990) recommended the use of the cubic root, where the shear stress is proportional to the cubic root of the concrete's compressive strength, as a better option than the use of the square root for high-strength concrete specimens with strength of more than 40 MPa.

Below are examples from three representative design codes: the American ACI 318-08 (2008), the Swiss SIA 262 (2003) and the Algerian CBA 93 (1993).

We chose the Swiss code, unlike the other European codes, because it supports many more parameters related to the punching phenomenon such as specified in the following developement.

3.1 Swiss code SIA 262 (2003)

The SIA 262 code recommends that the punching shear resistance, V_{rd}, to be expressed as proportional to $(F_{ck})^{1/3}$, where f_{ck} is the characteristic compressive strength of the highest-strength concrete ($F_{ck} \geq 30$ MPa). The influence of reinforcement ratio $\boldsymbol{\rho}$ and slab depth **d** is also considered in this code. The relevant characteristic resistance according to SIA 262 is

$$V_{rd}=K_r*\boldsymbol{\tau}_c*d*u \tag{1}$$

Where ($\boldsymbol{\tau}_c=0.2\sqrt{F_{ck}}$) is the nominal shear strength; **u** is the perimeter of the critical section at d/2; **d** is the slab effective depth; and ($\mathbf{K}_r=\frac{1}{0.45+0.9ry} \geq \frac{1}{1+2.2d}$) is a size factor of the effective depth end flexural capacity, where the radius of the yield zone is ($\mathbf{ry} = 0.15 * L * (\frac{mod}{mrd})^{1.5}$) ,if $\mathbf{F_{sd}}$>435MPa then **ry** must be increased by the factor $\mathbf{F_{sd}/435}$, ($\mathbf{m_{0d}}=V_d/8$) is the nominal moment capacity per unit width, and $\mathbf{m_{rd}}$ is the flexural capacity of the slab.

3.2 American code ACI 318-08 (2008)

A simple equation, developed based on the classical shear strength equation, is given for shear design in ACI-318. The control perimeter is only 0.5d from the loaded area, and the code does not consider the reinforcement ratio $\boldsymbol{\rho}$ or the effective depth **d** of the slab in limiting shear stress. ACI 318-08 requires that the ultimate shear resistance for slabs without shear reinforcement, **Vc**, be approximated by using the following expression

$$\boldsymbol{\phi}*V_n \geq Vc \tag{2}$$

and

$$Vn \leq \begin{cases} 0.083\left(2+{}^{4}/_{\beta}\right)\sqrt{Fc}.u.d \\ 0.083\left(\frac{\alpha s.d}{U}+2\right)\sqrt{Fc}.u.d \\ 0.083.4.\sqrt{Fc}.u.d \end{cases} \tag{3}$$

where **β** is ratio between the long side and the short side of the section, $\mathbf{F_c}$ is the concrete compressive strength and (**α**s = 40) for an interior column.

3.3 Algerian code CBA 93 (1993-2004)

In this code, a simple equation is applied in which the critical perimeter **U** is equal to **d/2** of the loading area

$$Vu \leq 0.045.u.h.Fc./\boldsymbol{\gamma b}\ldots \tag{4}$$

Where h = d + c + $\boldsymbol{\varphi}$, in which c represents the concrete coating and $\boldsymbol{\varphi}$ represents the diameter of the upper steel bar.

4. Fuzzy neural optimiser and punching

Neuro-adaptive networks are hybrid systems that combine the learning capacity of neural networks with the very powerful theory of fuzzy logic. The combination of these two approaches enables a researcher to exploit the characteristics of each to accomplish a task efficiently and effectively. Together, they have the power to obtain conclusions and generate responses from vague, imprecise and incomplete information when mathematical models are unknown or difficult to retrieve**.**

4.1 Architecture and learning

In this study, the architecture and learning procedure underlying ANFIS (Adaptive-Network-based Fuzzy Inference System) is exploited in the program, a fuzzy inference system implemented in the framework of adaptive networks Fig. 2 . By using a hybrid learning procedure, the proposed ANFIS constructs an input-output mapping based on both human knowledge (in the form of fuzzy if-then rules) and stipulated input-output data pairs. In the simulation, the ANFIS architecture is employed to model the punching shear of concentrically loaded interior slab-column connections without shear reinforcement and predict the ultimate rupture load by punching. The form of architecture most encountered in literature is ANFIS type3, the architecture based on the approximate reasoning of Takagi and Sugeno (1985, 1993). It is composed of a 5-layer adaptive network and a system of inference type3 (SIF). The weight and parameters are optimised by the algorithm of retro-propagation based on gradient descent.

We developed a fuzzy neural controller in the form of a program with different subroutines that determines the parameters of the input layer by identifying the most relevant physical and geometric variables in the behaviour of the rupture of slabs by punching.

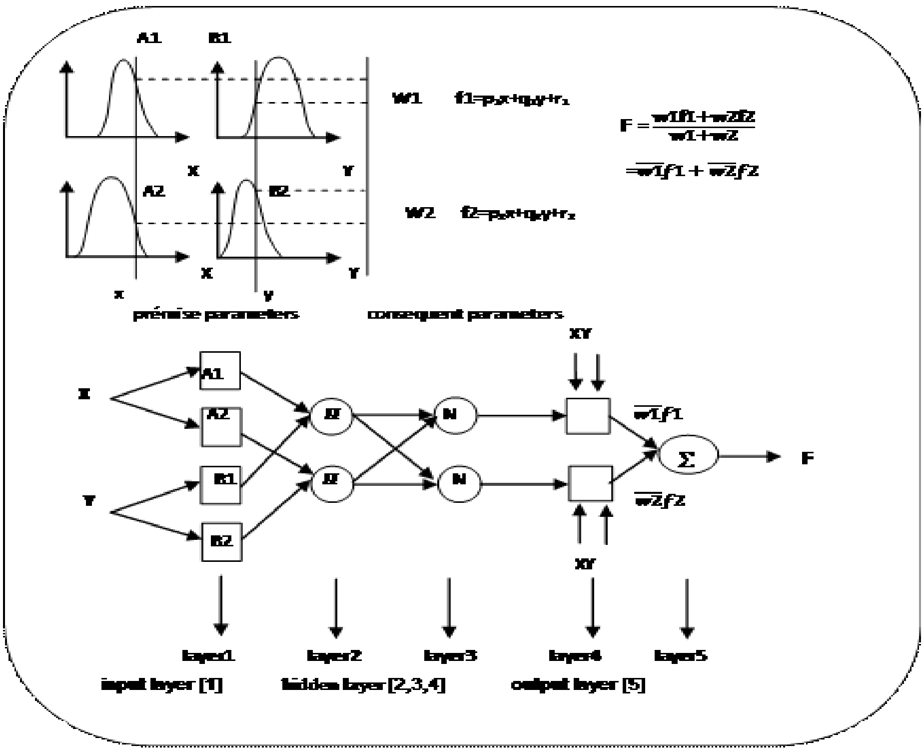

Fig. 2 The adaptive network architecture: ANFIS two-input type

Table 1 the most relevant physical and geometric variables in the behaviour of punching slabs

	The parameters of the input layers	The parameter of the output layer
d [mm]	Effective thickness of the slab	
$\mathbf{r_a}$ [mm]	Equivalent radius of the column	
$\mathbf{r_b/r_a}$	Ratio of the equivalent radius of the test slab to the equivalent radius of the column	
$\mathbf{F_c}$ [MPa]	Concrete compressive stress	***V_r* [KN]** the ultimate rupture load due to punching
U [mm]	Perimeter of critical section, measured at distance *d*/2 from column	
$\boldsymbol{\rho}$ [%]	Longitudinal reinforcement ration of slab	
$\mathbf{D_{max}}$[mm	Maximum diameter of aggregate	

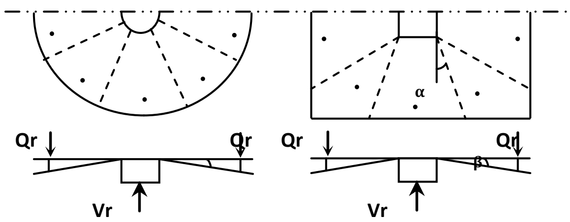

Fig. 3 Crack theory and flexural load crack

The effect of size on punching shear strength was introduced in this study using the ratio (r_b/r_a) corresponding to the equivalent ratio of the test slab and column.

Trials are often conducted on square slabs and columns and criteria are then established to understand the results for other geometries such as a circular slab. A perimeter test is used for equivalent columns

$$4.b=2.\boldsymbol{\pi}.ra \quad \Rightarrow \quad ra_{,eq}=2.b/\boldsymbol{\pi} \tag{5}$$

For slabs, the method of crack theory is used by analysing the mechanisms of square and circular slab equivalents Fig. 3 as follows

$$\sum \mathrm{We} = \sum \mathrm{Wi} \quad \Rightarrow \quad rb_{,eq} = \frac{2}{\pi} * [2 * (\sqrt{2} - 1) * (B - b) + b] \tag{6}$$

4.2 Database for punching trials

All samples are cases of punching slabs without shear reinforcement. A total of 280 experimental datasets were collected through specialised literature, a summary of which is shown in the Table 2. The learning process is conducted on a set of data named <terndada>, equivalent to 2/3 of the sample size, and the validation process is performed on 1/3 of the sample size in a file named <chekdata>.

Table 2 geometric and material properties of the studied specimens

Auteurs*	Number of spécimens n		Fc	.d	.b,	B	Dmax	ρ%
	Training	Validation	[MPa]	[mm]	[mm]	[mm]	[mm]	
Elstner/Hognestad 1956 (24)	15	10	10.1/ 39.9	114/ 121	254/ 356	1756	25/ 38	0.48/ 3.92
Nylander/Kinnunen 1960 (18)	11	7	24.3/ 31.0	117/ 128	150/ 300	1710	32	0.48 /2.18
Moe 1961(14)	10	4	19.5/ 33.4	114.3	152.4/ 254	1778	10/ 38.1	1.06/ 2.3
Yitzhaki 1966 (16)	12	4	9.2/ 21.3	79/ 82	119/ 333	1600/ 1667	/	0.53/ 2
Mantorola 1966 (12)	8	4	24.2/ 39.7	107	100/ 450	3000	16	0.5/ 2.6
Base 1966 (20)	15	5	13.3/ 39.3	102/ 124	203	1370	/	1/ 1.9
Corley/Hawkins 1968 (2)	1	1	42.2	203/ 254	111	1820	/	0.8/ 1.2
Ladner *et al.* 1973 (2)	2	0	33.2/ 37.7	109/ 240	226/ 500	1200/ 2650	32	1.05/ 1.23
Ladner *et al.* 1977 (4)	2	2	36.1/ 39.8	80	100/ 320	1056	16	1.46
Marti *et al.* 1977 (1)	1	0	34.6	145	300	2600	/	1.44
Schafers 1978 (2)	2	0	21.9/ 22.1	113/ 170	210	1680	32	0.5/ 0.7
ETH 1979/77 (2)	1	1	31.2/ 41	143/ 171	300	2600	16	1.44/ 1.66
Pralong *et al.* 1979 (1)	1	0	26.2	154	300	2600	/	1.34
Dierterle *et al.* 1978/1981 (13)	9	4	23.5/ 30.6	290/ 450	95/ 286	1510.6/ 2710	25	0.21/ 0.87
Swamy /Ali 1982 (2)	2	0	35.5/ 38.1	100	150	1690	10	0.5/ 0.6
Regan 1986/87 (24)	17	7	11.3/ 44.9	64/ 200	54/ 250	900/ 2745	5/ 20	0.6/ 1.6
Tolf 1988 (8)	5	3	22.6/ 28.2	98/ 200	125/ 250	1189/ 2378	16/ 32	0.37/ 0.92
Lovrovich/Mclean 1990 (5)	3	2	37.3	83	100	200/ 1200	19	1.48
Marzouk/Hussein 1991 (17)	12	5	28.5/ 76	70/ 120	150/ 300	1500	20	0.33/ 1.76
Tomaszewicz 1993 (13)	10	3	64.1/ 118.7	88/ 275	100/ 200	1100/ 2500	16	0.92/ 3.79
Ramdane 1993/96 (15)	11	4	26.5/ 100.3	98/ 102	150	1372	10/ 20	0.5/ 1
Hallgren 1996 (7)	4	3	79.9/ 103.4	194/ 202	250	2400	18	0.84/ 2.31
Hllegren *et al.* 1998 (11)	6	5	19.8/ 40	232/ 250	250	850/ 960	25	0.24/ 0.66
Kruger 1999 (1)	1	0	34.6	121	300	3000	16	1.3
Beutel/Hegger 2000 (8)	5	3	23.2/ 46.3	190/ 230	320/ 400	2400	/	0.8/ 1.75

Table 2 Continued

Hegger 2001 (4)	2	2	24/ 37	250	200/ 263	2400	/	0.8/ 1.25
Harajli *et al.* 2003 (4)	4	0	29.1/ 35.5	37/ 55	100	670	10	0.8/ 1.5
Binici *et al.* 2003(2)	1	1	28.3	114	304	1981	9.5	1.5/ 1.76
Sundquist/Kinnuen 2004a (8)	6	2	24/ 27.2	100/ 125	125/ 250	1190	/	0.64/ 0.8
Sundquist 2004b (3)	2	1	24.6/ 35.4	205/ 220	500/ 1000	1600	/	0.39/ 0.584
Tim 2004 (3)	2	1	32.8 /40.7	172 /246	175 /250	560 /800	/	1.18/ 1.25
Guandalini/Muttoni 2004 (11)	7	4	27.6/ 40.5	96/ 210	130/ 520	750/ 3221	4/ 16	0.25/ 1.5
Alam *et al.* 2009 (3)	1	2	31.4/ 35.8	54/ 74	120	1200	10	0.5/ 1
Total	**194**	**86**						

The limit of validity of the program is for the following values Table 3.

Table 3 The limit of validity of the program

	Margin of variable parameters				
Variable parameters	$\mathbf{F_{ck}}$ [MPa]	**d** [mm]	$\mathbf{D_{max}}$ [mm]	**rb/ra**	$\boldsymbol{\rho}$ [%]
Limit values	9.2/118.72	37/464	4/38.1	1.69/24.73	0.21/3.92

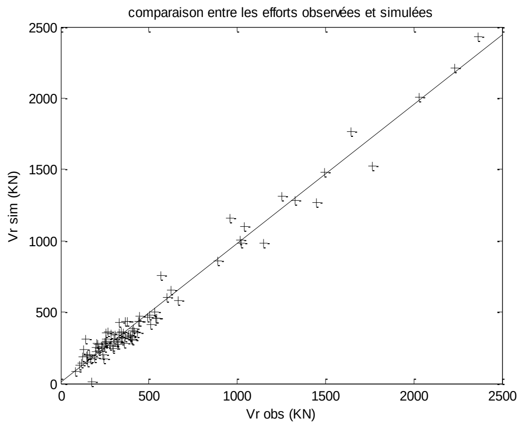

Fig. 4 Comparison between observed and simulated test data

After the input data were standardised, we compared the observed testing data and created a simulation using the fuzzy neural method. There is a great convergence between the values of the observed and simulated failure effort (R = 0. 99), shown in Fig. 4.

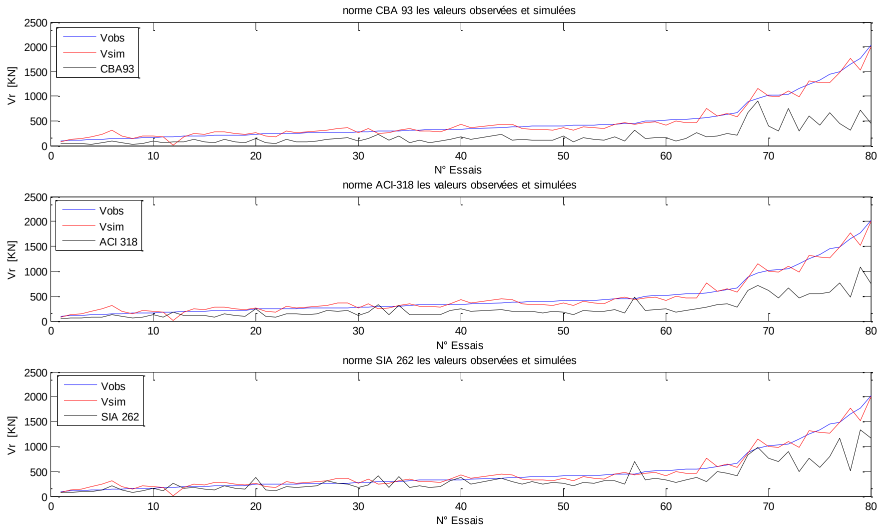

Fig. 5 Comparison of the simulated and observed values of the validation block <chekdata> and the calculated values of the codes *(a)Algérienne(CBA-93),*(b)Américaine(ACI- 318), ,*(c)Suisse(SIA-262)

5. Statistical analysis and validation criteria

Objective statistical criteria are used to broadly characterise the quality of the simulation. This component compares the failure of the observed shear $\mathbf{V_{obs}}$ to the calculated values from the codes and the simulated $\mathbf{V_{sim}}$ from predictive modelling using neurofuzzy. This work uses the following criteria:

5.1 Nash criterion

This criterion expresses the relationship between the simulated and observed values on error as a percentage, with the fluctuation of observed values reported as a mean

$$\mathbf{Nash=1 - \frac{\sum_{i=1}^{n}(Vi_{sim}-Vi_{obs})^2}{\sum_{i=1}^{n}(Vi_{obs}-\overline{Vi}_{obs})^2}} \tag{7}$$

more Nash criterion is closer to 1, more the model is better.

5.2 Error on the balance sheet

This criterion expresses the error between the observed and simulated values as a percentage:

$$\mathbf{Er=\frac{\sum_{i=1}^{n}(Vi_{obs}-Vi_{sim})}{\sum_{i=1}^{n}(Vi_{obs})}} \tag{8}$$

5.3 The coefficient of determination R^2

This criterion is expressed by R^2 and represents the correlation between the simulated and observed series

$$\mathbf{R}^2 = \frac{\sum_{i=1}^{n}[(Vi_{obs} - \bar{V}_{obs}) * (Vi_{sim} - \bar{V}_{sim})]^2}{\sum_{i=1}^{n}(Vi_{obs} - \bar{V}_{obs})^2 * \sum_{i=1}^{n}(Vi_{sim} - \bar{V}_{sim})^2} \quad (9)$$

To assess each method fairly, we performed a comparison of the rupture load $\mathbf{V_r}$ predicted from each code with the neurofuzzy method results, shown in Fig. 5 to Table (A.1).

The total results of comparison are shown in Table 4.

However, we cannot pronounce on this method, except if it simulates all of the data collected. So,we simulated each data of the learning block <terndata> inside the validation block <chekdata>.These simulated values are presented with error on each new sample <chekdata> and on the set of observed and simulated values, Table (A.3).

Notice first, that the error for each new sample rate remains stable and efficient despite the change of validation data, which proves the effectiveness of the program. Secondly, the validation criteria show a good convergence between the simulated and observed values Table (A.2). To better appreciate this second point, we compared the results obtained with the calculated values from the design standards shown in Fig. 6.

Table 4 comparison of the simulated and observed values of <chekdata=86 tests>

Tests [86]	SIA-262 Suisse [%]	ACI-318 american [%]	CBA- 93 algerian [%]	Neuro-fuzzy simulé [%]
Err	32.2	49.4	62.1	10.6
Nash	70.7	39.2	66.8	97.7
Rflou	92.3	93.4	83.6	98.8

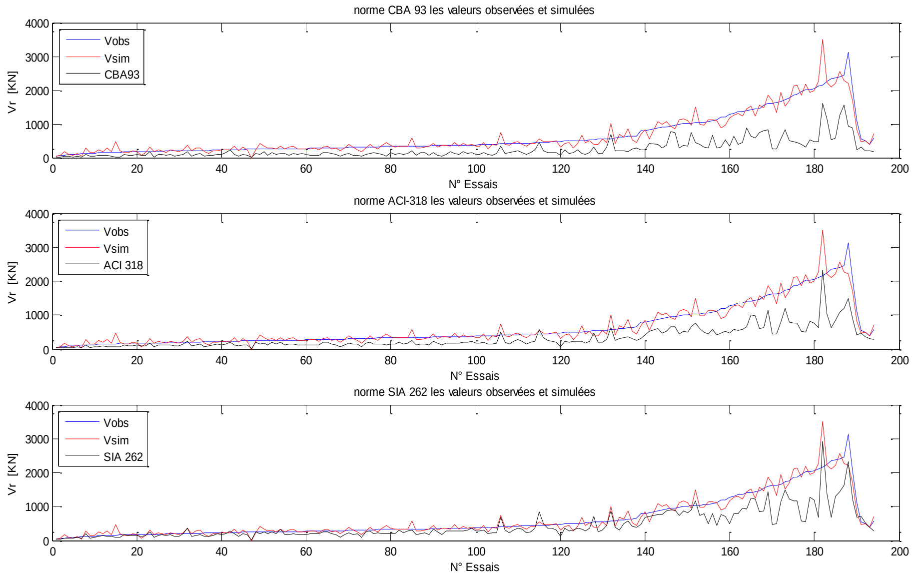

Fig. 6 Comparison of the simulated and observed values of the learning block and the calculated values of the codes *(a) Alg?rienne (CBA-93),*(b) Am?ricaine (ACI- 318),*(c) Suisse (SIA-262)

The total results of comparison are shown in Table 5.

Table 5 Comparison of the simulated and observed values of <terndata=194 tests>

Tests [194]	SIA-262 Suisse [%]	ACI-318 Amer [%]	CBA-93 Alger [%]	Neuro-Fuzzy simulé [%]
Err	34.7	62.3	62.3	15.7
Nash	62.2	11.2	10.8	91.1
Rflou	86.7	83.3	83.2	95.6

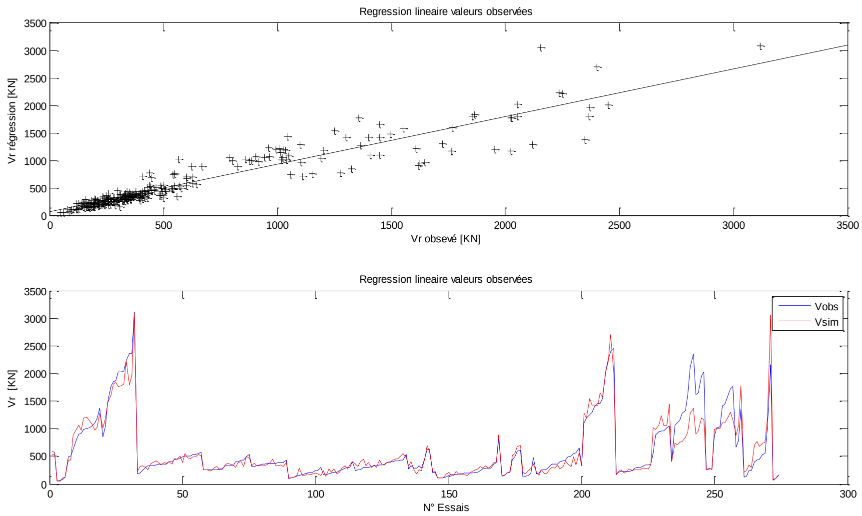

Fig. 7 Comparison of the observed values with the values predicted by the proposed Eq. (10)

6. Commentary

It is clear that the neurofuzzy simulation method has a small margin of error (10% to 15% on the validation sample in Tables 5-6) and a large convergence rate when compared to results from the design standards studied Figs. 5-6. The Swiss approach produces the most satisfactory result of all the studied codes Figs. 5(c)-6(c) because its formulation introduces all the parameters that influence punching.

However, to better assess this method, another approach more user-friendly and easier to use is presented.

7. Proposed equations for punching shear strength

The equation for the prediction of punching shear resistance was obtained using linear regression of the experimental data available in the literature. The formulation of the equation parameters by linear regression was based on the parametric neurofuzzy study of the size effect due to the ratio of slab to column dimensions **rb/ra**, the static height **d**, the aggregate size $\mathbf{D_{max}}$, the reinforcement ratio $\boldsymbol{\rho}$ and the characteristic concrete compression strength $\mathbf{F_c}$. After data analysis, exploration was performed on a sample of 277 tests, using several combinations of data to find that the parameters that most affect punching can be summarised in the following equation

$$\mathbf{V_r=61.4^{E-3}.(d)^{1.72}.\rho^{0.33}.(F_c)^{0.33}.(ra/rb)^{0.36}} \quad [KN] \tag{10}$$

The results of this equation are presented in the following graph Fig. 7 with an error of 17. The following Table 6 summarises the results obtained from this study.

Table 6 Summary of results from all samples

Erreur	Neurofuzzyu	Regression	The codes		
			CBA93 Algérie	ACI 318-08 Amérique	SIA262 Suisse
Err	13.15	17.78	62.2	55.85	33.45
Nash	94.4	88.39	38.8	25.2	66.45
Rflou	97.2	94.09	83.4	88.35	89.5

8. Conclusions

At the beginning of this study, we as designers were not convinced of the usefulness of a method that we had found to be unstable and, by its nature, random and subjective. Our objective was to better understand this approach through the experimental and simulated results obtained during our research.

Two new predictive design methods are presented. The first explored is a hybrid method based on neural networks with fuzzy learning called neurofuzzy. A total of 280 experimental datasets based on concentric punching shear tests taken from the literature have been exploited by the model (194 for learning and 86 for validation) and confirmed by statistical validation criteria. To better assess the quality and stability of the simulation, we run each data of block learning in the validation block (no value paired simultaneously in the two blocks) and estimated its error, the error associated with the entire simulated sample range. Very satisfactory results are obtained from this assessment, and the results were compared to representative design codes from around the world. The neurofuzzy model accurately predicted punching resistance with an average error of 13%, unlike all the design codes studied (ACI 318, SIA 262, CBA 93) where the error varied from 30 to 60%.

A second more user-friendly design method is presented, based on a model of the linear regression of parametric predictive modelling that supports all the geometric and material parameters affecting the punching phenomenon.

In conclusion, the neurofuzzy model can be taken as an alternative method, within its limits, to the simple empirical approaches used by different design codes. Despite its simplicity, the second equation developed (Eq. (10)) offers to the designer an accurate alternative to the equations presented in codes, with a competitive error of only 17 percent.

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Nomenclature

V_{rd} :punching shear resistance according to SIA- 262
V_c :ultimate shear resistance according to ACI- 318
V_u :shear force according to CBA 93
V_{obs}: experimental punching shear
V_{sim}: simulation punching shear
K_r :size factor of the effective depth for flexural capacity
d :distance from extreme compression fibre to centroid of longitudinal tensile reinforcement
τ_c :nominal shear strength provided by the concrete
r_y :radius of yield zone
F_{sd} :yield strength of reinforcement
D_{max}:maximum diameter of aggregate
Φ :strength reduction factor (according to North American practice, $\phi = 0.75$ for shear)
V_n :nominal punching shear strength according to ACI 318-08
F_c :compressive strength of concrete
F_{ck} :cylinder compressive strength
U :perimeter of critical section for punching shear, measured at distance $d/2$ from column face

h :slab thickness
φ :diameter of reinforcing steel
r_a :equivalent radius of column
r_b : equivalent radius of slab
ρ : flexural reinforcement ratio (%)of slab
L :slab span
b :column size
B :side dimension of test specimen
m_{od} :nominal moment capacity per unit width
m_{rd} :flexural capacity of slab
<terndata> : the learning block (194 tests)
<chekdata> : the validation block (86 tests)

Appendix: data tests and calculated results

Table [A.1] Comparison of observed and simulated values from the validation dataset <chekdata=86 tests>

calculation of code values on the block <chekdata>					simulation on the block validation <chekdata>		calculation of code values on the block <chekdata>					simulation on the block validation <chekdata>	
.d [mm]	Fc [MPa]	V_{SIA262}' [KN]	$V_{ACI318-08}$ [KN]	V_{CBA93} [KN]	Vobs' [KN]	'Vsim' [KN]	.d [mm]	Fc [MPa]	V_{SIA262}' [KN]	$V_{ACI318-08}$ [KN]	V_{CBA93} [KN]	Vobs' [KN]	'Vsim' [KN]
54	33	74.9	50.2	36.7	84.7	83	119	27.7	243	185	120.5	341	362.9
64	40.8	82.5	53	42.8	105	126.3	208	30	1341.1	1076	720.7	1763	1524.5
64	39.5	84.2	52.2	41.5	117	143.2	290	24.3	1164.3	751.3	451	2028	2003
95	11.3	93.7	71.5	29.9	123	185.3	120	64.6	355.9	234.6	233.1	365	436.5
83	37.3	117.9	72.6	55.4	129	235.6	114.3	24.1	296.9	192.2	116.9	378	435.2
102	34.7	204.4	125.7	92	141.4	310.3	114	31.2	243.5	185.4	128.1	384	338
99	24.8	132.8	86.4	53.5	148	196.3	114.3	23.3	291.6	188.8	112.8	392.3	334.5
82	9.6	75.1	60.3	23.4	152	147.2	120	28.5	236.4	155.8	102.8	396	322.4
93	14.2	101.9	77.7	36.4	154	201.7	118	20.6	279.9	185	103.9	400.3	313.5
107	37.2	152.3	119.7	90.5	164.8	200	98	83.2	265.6	173.3	196.5	405	368
74	35.8	117.3	78.6	59.1	172	173.4	124	25.1	205.8	133.1	82.4	408	305.8
114	11.2	262.6	169.4	70.2	178.4	12.6	124	33.6	282.5	215.1	154.1	409	386.6
77	32.6	156.8	114	81.6	194	182	117	31.2	251.9	191.8	132.4	419	364.8
70	66.5	176.8	116.5	119.6	196	250.7	114.3	19.8	308.7	199.7	109.8	432.8	351.2
95	27.6	146.2	111.5	72.8	197	223.3	124	39.3	305.5	232.6	180.2	439	436.4
83	37.3	123.4	72.6	55.4	204	282.2	114	17.9	249.3	164.8	86.2	444.8	470.4
98	55.5	205.7	141.5	131	212	274.6	210	28.5	699.5	474.4	309.7	445.4	433.4
93	31.8	152.7	116.5	81.9	214	244.6	120	29.1	329	212.8	142	490.5	464.1
100	28.2	143.7	93.4	61.6	216	230.9	114	34.7	355.4	229.7	167.4	504.9	476.9
121	20.7	374.9	247.3	139	235.8	256.5	114	28.3	320	237.7	156.5	510	413.3
80	17.4	123.5	99.1	51.7	239	201.2	114	20.9	270	178.5	101.1	533.8	501.5
82	17.7	113.2	81.7	43	245	170.1	119	29.1	325.5	210.5	140.5	539.6	459.4
93	50.6	192.6	147	130.3	248	291.8	120	70.3	371.3	244.7	253.6	543	460.1
100	24.4	182.6	135.2	83	250	254.6	154	26.2	293.3	279.8	176.1	569	757.5
117	27.6	198.4	128.2	83.3	255.1	281.4	199	22.6	488	332	193.1	600	602.5
125	26.6	214.4	138.6	88.3	258	296.4	171	31.2	464.3	351.5	240.7	626	653.2
123	25.5	317.8	205.5	128.2	258	313.5	172	36	410.9	280	206.1	668	584.3
114	36.4	263.1	200.3	149.6	259	353.9	194	81.4	831	607.7	671.3	889	857.2
111	42.2	251.1	208.3	167.6	266	359.1	201	103.4	985.3	720.6	896.3	960	1157.1
80	39.8	172.6	110.5	87.3	281	265.1	206	29	763.2	612.4	403.3	1017	1006.5
118	39	227.6	178.2	137.7	285	347.1	210	27.6	688.4	466.8	299.9	1023.5	984.6
107	32.5	415.7	324.4	229.3	294.3	245.2	200	87	897.6	656.4	749.3	1041	1103.8
98	43.1	181.2	124.7	101.7	297	261.6	190	27.3	495.9	457.9	293	1151	986.3
107	28.2	387.4	302.3	199.1	301.2	307	200	80.1	755.5	547.3	599.4	1250	1314.3
121	13.5	173.2	131.9	59.9	307	341.3	190	37.9	584.3	539.6	406.8	1326	1283.7
95	39.9	203.6	134.2	105.5	320	291.7	200	89.3	797.6	577.8	668.1	1450	1267.2
114	15.5	171.7	130.7	63.7	322	294	294	23.6	1170.1	755.1	446.6	1493	1483.1
80	38	192.7	123.4	95.2	324	275.1	250	29.2	514.5	475.3	313.3	1646	1769
120	26.5	313.9	203	129.3	331.6	350.9	208	30	1341.1	1076	720.7	1763	1524.5
114	37.7	370.4	239.4	181.9	333.6	426.4	290	24.3	1164.3	751.3	451	2028	2003

Tests [86]	SIA 262 [%]	ACI 318 [%]	CBA 93 [%]	Fuzzy-flou [%]
Err	32.2	49.4	62.1	10.6
Nash	70.7	39.2	66.8	97.7
Rflou	92.3	93.4	83.6	98.8

Table [A.2] Comparison of observed and simulated values on the learning block <terndata>

comparison of the simulated values of the learning block and the calculated values of the codes Américaine(ACI), Algérienne(CBA),Suisse(SIA)								comparison of the simulated values of the learning block and the calculated values of the codes Américaine(ACI), Algérienne(CBA),Suisse(SIA)							
N°	.d [mm]	Fc [MPa]		V_{SIM} [KN]	V_{CBA93} [KN]		V_{SIA262} [KN]	N°	.d [mm]	Fc [Mpa]		V_{SIM} [KN]	V_{CBA93} [KN]		V_{SIA262} [KN]
1	37	31.9	49.2	49.7	19.8	26.9	43.3	64	118	38.2	280	320.5	145.8	190.7	243.9
2	37	35.5	60.5	69.1	22.1	28.3	45.6	65	107	31.4	282.5	332.5	138.4	199.3	254.3
3	55	35.5	78.8	164.7	35.4	46.7	75.3	66	118	43	285	264.9	121.8	150.1	191.3
4	54	31.4	91.8	98.8	34.9	48.9	73	67	98	41.4	286	291.2	97.8	122.3	187.4
5	82	11.5	98	70.4	18.6	43.8	54.5	68	80	35.6	288	208.7	50.2	67.2	105
6	64	42.9	105	129.9	45	54.4	82.1	69	100	37.1	294	276.5	90.2	119.1	182.5
7	82	9.9	117	38.1	15.9	40.5	56.1	70	117	25.9	298	399.4	110.2	175	229.8
8	102	34.7	118	291.1	92	125.7	204.4	71	119	15.2	298	309.1	66	137	179.9
9	55	29.1	122	143.1	29.1	42.3	68.2	72	118	11.1	302.5	242.9	56.1	136	205.7
10	78	10.8	128	144.5	27.6	67	93.6	73	83	14.8	307	184.2	34	70.8	98.1
11	83	37.3	139	242.2	55.4	72.6	112.8	74	114.3	19.5	312	291.8	94.3	172.7	266.8
12	98	26.3	145	188.3	55.9	87.6	134.8	75	114.3	25.3	312	379.7	122.4	196.7	272.8
13	83	37.3	149	274.3	55.4	72.6	120.6	76	98	59.7	319	299.9	140.9	146.8	213.3
14	82	17	152	165.8	41.3	80.1	110.9	77	80	36.1	324	250.5	113.1	150.3	234.8
15	79	9.2	157	469.5	23.7	62.6	87.5	78	121	19.6	328	362.6	86.9	158.9	208.7
16	82	9.7	162	200.4	26.3	67.6	94.4	79	114	10.7	329.2	436.9	51.5	127.4	197.1
17	79	33.4	165	148.4	86.3	119.2	164	80	88	84.9	330	368.9	156.9	136.5	212.7
18	79	26	165	158.8	67.2	105.2	144.7	81	122	28.4	331.6	323.5	91.2	138.4	214
19	98	26.5	169	205.7	62.7	97.9	142.3	82	122	24.3	331.6	336.1	120.6	198.2	306.6
20	118	40.8	170	182.1	86.9	110	140	83	121	31.1	333.5	346.5	98.4	142.9	221
21	107	25.1	175.1	60.4	61	98.2	125	84	114.3	22.6	334	345.6	109.5	186.1	287.4
22	77	27.8	176	137.3	69.7	105.4	144.9	85	111	42.2	334	585.9	197	244.9	295.8
23	95	63.6	178	302.5	168.3	169.5	257.2	86	102	18.3	336	275	65.5	123.2	161.7
24	82	10.4	181	178.5	25.1	62.5	86.6	87	98	60	341	277.1	141.8	147.2	214
25	107	37.7	184.4	235.4	91.7	120.4	153.2	88	100	55.7	341	321.2	135.3	145.9	223.5
26	79	36.1	186	191.9	93.2	123.9	170.4	89	117	14.7	346	335.3	62.6	131.9	173.2
27	77	30.6	194	161.5	76.6	110.5	151.9	90	118	29.1	351.4	432.1	146.5	219.6	332.3
28	77	38.4	194	217.6	96.1	123.7	170.2	91	118	16	355.9	319.4	80.8	163.2	246.8
29	99	22.6	194	212.2	48.7	82.4	126.7	92	114	10.1	355.9	370.2	48.8	124	187.6
30	107	23	196.2	173.2	55.9	94	119.6	93	114.3	21	355.9	359.1	101.7	179.3	277
31	100	38.1	198	232.4	107.7	140.5	196.5	94	95	70.3	356	334.3	185.9	178.2	270.3
32	114	37.6	200.2	365	181.5	239.2	370	95	109	37.7	362	459	133.5	175.3	282.5
33	82	17.9	201	212.8	43.4	82.1	113.7	96	114.3	21.5	364	328.8	104	181.3	280.1
34	107	34	210.9	290.2	82.7	114.4	145.5	97	128	40.8	365	416.8	167.1	212	292.4
35	95	44.9	214	295.9	118.8	142.4	186.7	98	114.3	24.8	371.4	355.6	120.1	194.9	301
36	82	13.8	215	182.1	37.3	80.4	112.3	99	114.3	33.4	374	398.8	162	226.3	349.5
37	107	24.3	215.8	112.2	59.1	96.7	123	100	114.3	21.9	378.1	328.2	105.8	182.9	282.5
38	82	18.5	218	201.8	61.5	114.4	158.5	101	114.3	22.1	389.2	327.4	107.2	184.1	284.4
39	100	35.5	222	213	100.5	135.7	189.8	102	128	39.5	390	438.9	162	208.8	307.3
40	102	33.3	227	231.5	83	115.9	177.6	103	114.3	26.2	394	247.7	89.5	141.1	195.2
41	98	58	233	236.1	137	144.7	210.3	104	114	15.4	400.3	390.3	74.4	153.1	231.6
42	98	100.3	233	223.5	237	190.3	276.6	105	117	27.8	402	359.8	118.3	181.3	238.1
43	96	34.7	235.9	325.6	84.8	115.7	188.1	106	210	32.2	407.5	742.7	349.9	504.2	673.3
44	82	21.3	240	206.5	51.8	89.7	111.8	107	124	24.3	408.1	391.7	123.5	202.8	313.6
45	100	34.7	242.5	307	89.5	122.3	198.9	108	90	62.7	418	358.4	154.6	156.6	237.6
46	100	32.5	244	228.8	78.9	111.4	161.9	109	124	37.3	419	437.6	171.1	226.7	297.7
47	82	13.3	244	0	8.8	19.2	22.6	110	121	34.6	423	479.4	203.6	280	357.7
48	107	29.7	245.9	227.2	131.3	194.1	247.7	111	128	25.6	429.7	389.8	135.3	216.7	335.2
49	124	17.9	247	423.4	81.8	156.8	205.9	112	128	26.4	430	337.2	90.7	143	221.1
50	95	66.5	249	348.1	175.8	173.3	262.9	113	121	30.9	430	426.9	137.1	199.6	262.1

Table [A.2] Continued

51	117	26.8	255	294.3	81	126.4	195.6	114	120	65.5	436	428	236.5	236.3	358.5
52	107	32.1	257	296.5	141.7	201.7	257.4	115	210	40.5	438.7	541	440	565.5	833.9
53	123	26.3	258	265.6	85.3	134.6	208.2	116	197	23.9	444	478.6	201.1	336.3	494.3
54	125	25.8	258	328.3	132.5	211.1	326.5	117	114	23.6	444.8	473.8	147.9	245.8	372.7
55	70	71.2	258	264	128.1	120.6	183	118	170	22.1	460	465.1	137.2	237.7	368.4
56	124	13.3	259	321.6	60.9	135.3	177.7	119	114	29.6	467.1	490.1	142.7	212	320.7
57	118	38.5	265	332	113.3	147.7	188.4	120	83	37.3	480	306.1	55.4	72.6	126.4
58	125	27.2	265	250.2	82.1	127.4	172.1	121	120	66.5	489	413.1	239.9	238	361.1
59	70	64.6	267	256.8	116.2	114.8	174.2	122	114	23.5	489.3	454.1	113.3	188.9	285.8
60	100	24	270	257.3	81.6	134.1	181.1	123	114	28.3	494	280.5	156.5	237.7	320
61	118	25.4	274.7	269.9	77.8	124.7	192.9	124	95	68.4	498	424.1	237.2	230.5	350.2
62	118	26.2	275	281.8	80.1	126.6	195.7	125	114	19.8	498.2	672.5	123.7	224.8	340.8
63	113	22	280	226.1	77.6	133.7	207.3	126	114	22	511.5	447.6	106.4	183.1	277
127	114	22	533.8	511.4	137.5	237	359.4	142	290	28.1	859	0	373.3	578.2	893.6
128	210	28.5	539.9	401.1	309.7	474.4	699.5	143	208	27.7	875	1077.5	390	606	755.3
129	117	30.6	541	393.5	130	190	249.6	144	244	25.5	904	994.2	293.2	475.9	771.3
130	114	27.3	547.1	551.4	131.6	203.6	308.1	145	245	31.4	915	1063.1	363.3	531.3	861.2
131	95	67.4	560	436.3	297.5	291.1	443	146	198	89.3	944	937.6	757.9	655.4	896.2
132	202	79.9	565	1015.1	697.8	638.1	872.6	147	200	85.8	965	863.1	738.7	651.8	891.2
133	114	39.9	578.3	420.8	192.6	246.4	381.2	148	232	25.7	992	1110.8	274.4	443.2	725.9
134	145	34.6	600	678	214.8	296.8	311.1	149	250	29.8	1008	1160	355.3	533.5	873.8
135	200	23.9	603	620.3	206.1	344.3	506.1	150	243	28.4	1015	1101.5	324.6	499.2	817.5
136	246	14.4	622	860.9	167.6	362	586.7	151	200	86.7	1021	962	746.9	655.4	896.2
137	143	41	628	522.2	250.2	317.3	419.1	152	296	23.5	1034	1493.4	449.1	760.8	1179.1
138	120	76	645	456	274.2	254.4	386	153	210	26.7	1039	977	380.6	602.4	750.8
139	172	40.7	789	683.7	233	297.7	461.6	154	242	27.3	1049	968	310.1	486.4	788.3
140	244	19.8	803	834.6	227.7	419.4	679.7	155	190	26.2	1055	1133.1	281.2	448.6	485.8
141	200	41.4	825	545.2	410.9	521.8	703.7	156	200	88	1100	1130.3	658.3	573.6	791.8
142	290	28.1	859	0	373.3	578.2	893.6	157	190	29.8	1109	1100.8	276.5	413.6	447.7
143	208	27.7	875	1077.5	390	606	755.3	158	235	28.2	1190	887.9	306.8	473.2	767
144	244	25.5	904	994.2	293.2	475.9	771.3	159	200	70	1200	952.1	524	511.7	706.3
145	245	31.4	915	1063.1	363.3	531.3	861.2	160	190	37.5	1276	1173	347.9	463.9	502.2
146	198	89.3	944	937.6	757.9	655.4	896.2	161	200	86.5	1300	1263.3	647.1	568.7	785
147	200	85.8	965	863.1	738.7	651.8	891.2	162	246	32.8	1356	1302.6	381.8	546.4	802
148	232	25.7	992	1110.8	274.4	443.2	725.9	163	242	40	1363	1231.4	454.4	588.8	964.3
149	250	29.8	1008	1160	355.3	533.5	873.8	164	200	118.7	1400	1448.4	888.2	666.3	919.7
150	243	28.4	1015	1101.5	324.6	499.2	817.5	165	205	26.6	1406	1523.6	628.4	996.1	1241.5
151	200	86.7	1021	962	746.9	655.4	896.2	166	209	24.6	1448	1234.9	594.3	979.9	1221.3
152	296	23.5	1034	1493.4	449.1	760.8	1179.1	167	200	97.8	1450	1567.4	731.5	604.7	834.6
153	210	26.7	1039	977	380.6	602.4	750.8	168	200	107.8	1550	1461.7	806.9	635	876.5
154	242	27.3	1049	968	310.1	486.4	788.3	169	205	35.4	1607	1856.8	836.3	1149.1	1432.2
155	190	26.2	1055	1133.1	281.2	448.6	485.8	170	250	24	1616	1684.6	257.5	430.9	466.5
156	200	88	1100	1130.3	658.3	573.6	791.8	171	220	23.2	1624	1340	263.3	447.4	484.3
157	190	29.8	1109	1100.8	276.5	413.6	447.7	172	240	33.2	1661.8	1938.7	562	799.6	1152.3
158	235	28.2	1190	887.9	306.8	473.2	767	173	220	32.6	1725	1522.9	835.9	1198.2	1493.4
159	200	70	1200	952.1	524	511.7	706.3	174	294	25.9	1765	1694.7	490.2	791	1225.8
160	190	37.5	1276	1173	347.9	463.9	502.2	175	290	24.8	1853	2112	460.3	759	1176.2
161	200	86.5	1300	1263.3	647.1	568.7	785	176	292	24.1	1865	2139.8	451.7	755.6	1171
162	246	32.8	1356	1302.6	381.8	546.4	802	177	250	37	1954	1861.5	397	535	579.2
163	242	40	1363	1231.4	454.4	588.8	964.3	178	250	25.3	2024	2183	309.5	504.4	546
164	200	118.7	1400	1448.4	888.2	666.3	919.7	179	293	28.1	2025	1942.3	529.2	819.9	1270.6
127	114	22	533.8	511.4	137.5	237	359.4	180	292	25.3	2050	1995.8	474.2	774.2	1199.8
128	210	28.5	539.9	401.1	309.7	474.4	699.5	181	230	40	2117	2269.7	483.1	625.5	677.2
129	117	30.6	541	393.5	130	190	249.6	182	464	32.4	2153.4	3504.9	1605.9	2326.1	2922

Table [A.2] Continued

130	114	27.3	547.1	551.4	131.6	203.6	308.1	183	275	83.5	2250	2227.3	1158.8	1040.8	1394.1
131	95	67.4	560	436.3	297.5	291.1	443	184	220	46.3	2349	2098.7	525.5	632	684.2
132	202	79.9	565	1015.1	697.8	638.1	872.6	185	290	30.6	2368	2209	567.9	843.1	1306.5
133	114	39.9	578.3	420.8	192.6	246.4	381.2	186	275	89.7	2400	2559.3	1244.7	1078.7	1444.9
134	145	34.6	600	678	214.8	296.8	311.1	187	275	111.7	2450	2279.5	1550.6	1204	1612.7
135	200	23.9	603	620.3	206.1	344.3	506.1	188	450	26.2	3116	2208.6	930.6	1498.7	2322.5
136	246	14.4	622	860.9	167.6	362	586.7	189	275	64.1	2050	1692	890.2	912.3	1221.9
137	143	41	628	522.2	250.2	317.3	419.1	190	240	21.4	1103	812.6	240.1	425.3	689.4
138	120	76	645	456	274.2	254.4	386	191	210	29.3	550	465	318.4	481	709.3
139	172	40.7	789	683.7	233	297.7	461.6	192	200	25	489	492.5	215.6	352.1	517.6
140	244	19.8	803	834.6	227.7	419.4	679.7	193	107	30.3	397.3	386.4	213.9	313.3	401.5
141	200	41.4	825	545.2	410.9	521.8	703.7	194	154	26.2	569	707.9	176.1	279.8	293.3
						194 tests [%]	Neuro Flou	93 Alger	ACI 318 Amer	SIA 262 suisse					
						Err	15.7	62.3	62.3	34.7					
						Nash	91.1	10.8	11.2	62.2					
						Rflou	95.6	83.2	83.3	86.7					

Table [A.3] Simulation of the data from the learning dataset block <terndata>

N° of Spéci mens	simulation on each data of learning block in the validation sample				Error on validation sample			N° Essai	simulation on each data of learning block in the validation sample				Error on validation sample		
K	.d [mm]	Fc [MPa]	Vobs [KN]	Vsim [KN]	'Err' %	Nash %'	'Rflou' %	K	.d [mm]	Fc [MPa]	Vobs [KN]	Vsim [KN]	'Err' %	Nash %'	'Rflou' %
1	37	31.9	49.2	49.7	15.8	92.5	96.2	61	118	25.4	274.7	269.9	11.6	96.9	98.5
2	37	35.5	60.5	69.1	12.5	96.8	98.5	62	118	26.2	275	281.8	11.3	97.5	98.8
3	55	35.5	78.8	164.7	13.8	94.5	97.5	63	113	22	280	226.1	12.5	97.0	98.6
4	54	31.4	91.8	98.8	14.4	92.9	96.5	64	118	38.2	280	320.5	11.5	97.3	98.7
5	82	11.5	98	70.4	12.8	96.5	98.2	65	107	31.4	282.5	332.5	16.5	93.4	96.6
6	64	42.9	105	129.9	11.7	97.2	98.6	66	118	43	285	264.9	12.9	96.3	98.4
7	82	9.9	117	0	33.6	104.2	48.3	67	98	41.4	286	291.2	13.5	94.0	97.5
8	102	34.7	118	291.1	14.3	95.8	97.9	68	80	35.6	288	208.7	11.8	96.9	98.5
9	55	29.1	122	143.1	17.6	92.4	96.2	69	100	37.1	294	276.5	12.7	95.4	98.0
10	78	10.8	128	144.5	11.5	96.0	98.1	70	117	25.9	298	399.4	13.6	95.9	98.0
11	83	37.3	139	242.2	13.7	96.0	98.1	71	119	15.2	298	309.1	11.5	97.5	98.8
12	98	26.3	145	188.3	15.8	94.7	97.3	72	118	11.1	302.5	242.9	11.6	97.3	98.6
13	83	37.3	149	274.3	11.3	97.7	98.8	73	83	14.8	307	184.2	15.1	94.1	97.1
14	82	17	152	165.8	11.9	97.0	98.6	74	114.3	19.5	312	291.8	14.6	95.2	97.7
15	79	9.2	157	469.5	15.7	93.7	97.0	75	114.3	25.3	312	379.7	16.8	91.5	95.7
16	82	9.7	162	200.4	15.6	92.6	96.3	76	98	59.7	319	299.9	13.0	95.2	97.7
17	79	33.4	165	148.4	11.6	97.2	98.6	77	80	36.1	324	250.5	12.2	97.2	98.7
18	79	26	165	158.8	13.2	96.6	98.3	78	121	19.6	328	362.6	15.3	92.4	96.8
19	98	26.5	169	205.7	11.6	97.4	98.7	79	114	10.7	329.2	436.9	13.8	93.1	97.1
20	118	40.8	170	182.1	12.7	95.6	98.1	80	88	84.9	330	368.9	12.3	96.4	98.3
21	107	25.1	175.1	60.4	12.7	96.9	98.5	81	122	28.4	331.6	323.5	13.1	93.2	97.3
22	77	27.8	176	137.3	16.7	92.8	96.4	82	122	24.3	331.6	336.1	12.9	96.0	98.0
23	95	63.6	178	302.5	13.4	96.4	98.2	83	121	31.1	333.5	346.5	13.7	95.7	97.8
24	82	10.4	181	178.5	11.6	96.8	98.5	84	114.3	22.6	334	345.6	23.1	59.4	79.9
25	107	37.7	184.4	235.4	13.4	96.0	98.1	85	111	42.2	334	585.9	17.5	91.2	95.6
26	79	36.1	186	191.9	12.0	96.9	98.5	86	102	18.3	336	275	12.0	97.3	98.6
27	77	30.6	194	161.5	12.4	96.6	98.5	87	98	60	341	277.1	11.0	97.6	98.8
28	77	38.4	194	217.6	11.1	97.6	98.8	88	100	55.7	341	321.2	13.0	93.9	97.5
29	99	22.6	194	212.2	14.1	94.5	97.6	89	117	14.7	346	335.3	10.9	97.7	98.8

Table [A.3] Continued

30	107	23	196.2	173.2	12.4	96.8	98.4	90	118	29.1	351.4	432.1	11.2	97.3	98.7
31	100	38.1	198	232.4	12.7	96.4	98.3	91	118	16	355.9	319.4	14.7	95.5	97.8
32	114	37.6	200.2	365	12.7	96.8	98.4	92	114	10.1	355.9	370.2	12.7	96.3	98.3
33	82	17.9	201	212.8	12.1	96.8	98.5	93	114.3	21	355.9	359.1	14.5	93.5	96.8
34	107	34	210.9	290.2	12.2	96.5	98.4	94	95	70.3	356	334.3	12.3	96.5	98.4
35	95	44.9	214	295.9	13.6	96.1	98.2	95	109	37.7	362	459	15.3	94.6	97.4
36	82	13.8	215	182.1	12.4	96.0	98.2	96	114.3	21.5	364	328.8	14.0	95.0	97.7
37	107	24.3	215.8	112.2	10.7	97.8	98.9	97	128	40.8	365	416.8	13.5	95.9	98.0
38	82	18.5	218	201.8	19.6	57.4	89.8	98	114.3	24.8	371.4	355.6	15.0	95.5	97.7
39	100	35.5	222	213	12.1	96.5	98.4	99	114.3	33.4	374	398.8	15.0	91.8	96.6
40	102	33.3	227	231.5	13.8	96.0	98.2	100	114.3	21.9	378.1	328.2	11.4	97.4	98.7
41	98	58	233	236.1	15.0	92.8	96.5	101	114.3	22.1	389.2	327.4	12.5	95.9	98.0
42	98	100.3	233	223.5	13.0	96.6	98.4	102	128	39.5	390	438.9	11.6	96.9	98.6
43	96	34.7	235.9	325.6	13.9	96.0	98.0	103	114.3	26.2	394	247.7	12.5	97.0	98.5
44	82	21.3	240	206.5	12.1	96.9	98.4	104	114	15.4	400.3	390.3	13.0	96.5	98.4
45	100	34.7	242.5	307	12.9	96.1	98.2	105	117	27.8	402	359.8	12.9	96.5	98.4
46	100	32.5	244	228.8	12.4	97.0	98.5	106	210	32.2	407.5	742.7	15.5	93.3	96.6
47	82	13.3	244	0	0.0	0.0	5.1	107	124	24.3	408.1	391.7	13.1	96.3	98.3
48	107	29.7	245.9	227.2	12.9	96.8	98.4	108	90	62.7	418	358.4	11.5	97.3	98.7
49	124	17.9	247	423.4	15.9	90.6	96.3	109	124	37.3	419	437.6	12.5	97.1	98.6
50	95	66.5	249	348.1	13.1	96.6	98.3	110	121	34.6	423	479.4	16.0	92.5	96.3
51	117	26.8	255	294.3	11.1	97.7	98.8	111	128	25.6	429.7	389.8	12.2	96.6	98.3
52	107	32.1	257	296.5	12.0	97.2	98.8	112	128	26.4	430	337.2	11.4	97.5	98.8
53	123	26.3	258	265.6	13.7	96.2	98.2	113	121	30.9	430	426.9	13.5	94.0	97.3
54	125	25.8	258	328.3	12.5	96.4	98.2	114	120	65.5	436	428	15.5	94.2	97.1
55	70	71.2	258	264	18.3	81.9	91.6	115	210	40.5	438.7	541	11.9	96.8	98.5
56	124	13.3	259	321.6	12.3	96.1	98.3	116	197	23.9	444	478.6	11.1	97.6	98.8
57	118	38.5	265	332	16.5	93.0	96.6	117	114	23.6	444.8	473.8	12.3	96.7	98.4
58	125	27.2	265	250.2	11.5	97.0	98.6	118	170	22.1	460	465.1	13.4	95.3	97.7
59	70	64.6	267	256.8	11.9	97.2	98.6	119	114	29.6	467.1	490.1	14.9	94.0	97.0
60	100	24	270	257.3	11.6	97.3	98.7	120	83	37.3	480	306.1	17.2	91.5	95.7
121	120	66.5	489	413.1	12.6	96.0	98.2	158	235	28.2	1190	887.9	17.0	92.3	96.3
122	114	23.5	489.3	454.1	13.4	93.6	97.2	159	200	70	1200	952.1	13.0	94.9	97.7
123	114	28.3	494	280.5	15.2	93.6	96.8	160	190	37.5	1276	1173	15.3	93.0	96.5
124	95	68.4	498	424.1	11.6	97.5	98.7	161	200	86.5	1300	1263.3	12.6	97.0	98.7
125	114	19.8	498.2	672.5	13.6	95.7	97.8	162	246	32.8	1356	1302.6	12.8	96.7	98.5
126	114	22	511.5	447.6	16.4	88.2	95.5	163	242	40	1363	1231.4	12.8	94.7	97.4
127	114	22	533.8	511.4	16.3	92.9	96.6	164	200	118.7	1400	1448.4	12.3	96.9	98.5
128	210	28.5	539.9	401.1	13.3	95.3	97.9	165	205	26.6	1406	1523.6	16.8	91.3	95.6
129	117	30.6	541	393.5	13.2	95.3	98.0	166	209	24.6	1448	1234.9	11.2	97.3	98.7
130	114	27.3	547.1	551.4	12.2	97.0	98.6	167	200	97.8	1450	1567.4	10.9	97.4	98.8
131	95	67.4	560	436.3	13.7	95.7	98.0	168	200	107.8	1550	1461.7	12.3	97.0	98.5
132	202	79.9	565	1015.1	13.8	93.9	97.5	169	205	35.4	1607	1856.8	12.6	95.6	98.3
133	114	39.9	578.3	420.8	13.6	95.1	97.8	170	250	24	1616	1684.6	14.1	93.7	96.9
134	145	34.6	600	678	11.8	97.3	98.6	171	220	23.2	1624	1340	17.5	90.8	95.4
135	200	23.9	603	620.3	11.8	96.9	98.5	172	240	33.2	1661.8	1938.7	15.9	93.7	96.8
136	246	14.4	622	860.9	13.2	94.8	97.8	173	220	32.6	1725	1522.9	17.5	91.1	95.5
137	143	41	628	522.2	16.4	92.9	96.5	174	294	25.9	1765	1694.7	14.3	95.6	97.8
138	120	76	645	456	12.3	96.6	98.4	175	290	24.8	1853	2112	15.3	94.9	97.4
139	172	40.7	789	683.7	13.9	96.1	98.1	176	292	24.1	1865	2139.8	14.8	95.5	97.8
140	244	19.8	803	834.6	12.4	96.7	98.4	177	250	37	1954	1861.5	11.6	97.4	98.7
141	200	41.4	825	545.2	19.6	86.2	94.4	178	250	25.3	2024	2183	12.8	96.7	98.4
142	290	28.1	859	0	14.4	92.0	96.3	179	293	28.1	2025	1942.3	14.9	93.1	96.6
143	208	27.7	875	1077.5	13.4	95.8	97.9	180	292	25.3	2050	1995.8	12.2	97.2	98.6

Table [A.3] Continued

144	244	25.5	904	994.2	11.3	97.5	98.8	181	230	40	2117	2269.7	11.9	96.9	98.6
145	245	31.4	915	1063.1	12.1	96.5	98.3	182	464	32.4	2153.4	3504.9	14.1	89.4	95.5
146	198	89.3	944	937.6	16.0	91.8	95.9	183	275	83.5	2250	2227.3	10.9	97.6	98.8
147	200	85.8	965	863.1	13.4	96.3	98.3	184	220	46.3	2349	2098.7	13.9	94.0	97.1
148	232	25.7	992	1110.8	14.2	95.4	97.7	185	290	30.6	2368	2209	13.9	95.8	98.0
149	250	29.8	1008	1160	15.4	91.2	96.3	186	275	89.7	2400	2559.3	11.0	97.7	98.9
150	243	28.4	1015	1101.5	13.4	94.2	97.6	187	275	111.7	2450	2279.5	12.8	96.6	98.4
151	200	86.7	1021	962	11.1	97.5	98.8	188	450	26.2	3116	2208.6	14.1	94.2	98.0
152	296	23.5	1034	1493.4	14.5	95.3	97.8	189	275	64.1	2050	1692	10.6	97.5	98.8
153	210	26.7	1039	977	11.3	97.3	98.8	190	240	21.4	1103	812.6	14.0	95.4	97.7
154	242	27.3	1049	968	12.1	96.7	98.4	191	210	29.3	550	465	11.3	97.4	98.7
155	190	26.2	1055	1133.1	12.3	96.7	98.4	192	200	25	489	492.5	13.8	95.7	97.8
156	200	88	1100	1130.3	16.6	92.1	96.1	193	107	30.3	397.3	386.4	14.5	91.8	96.9
157	190	29.8	1109	1100.8	12.3	96.1	98.2	194	154	26.2	569	707.9	12.4	96.1	98.3